A Resource Booklet for SACE Stage 1 Earth and Environmental Science

The following pages have been prepared by practicing teachers of SACE Earth and Environmental Science. The six Chapters are aligned with the six topics described in the SACE Stage 1 subject outline. They aim to provide an additional source of contexts and ideas to help teachers plan to teach this subject.

For further information, including the general and assessment requirements of the course see: https://www.sace.sa.edu.au/web/earth-and-environmental-science/stage-1/planning-to-teach/subject-outline

A Note for Teachers
The resources in this booklet are not intended for 'publication'. They are 'drafts' that have been developed by teachers for teachers. They can be freely used for educational purposes, including course design, topic and lesson planning. Each Chapter is a living document, intended for continuous improvement in the future. Teachers of Earth and Environmental Science are invited to provide feedback, particularly suggestions of new contexts, field-work and practical investigations that have been found to work well with students. Your suggestions for improvement would be greatly appreciated and should be directed to our project coordinator:: lenaltman9@gmail.com

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SOUTH AUSTRALIA

Government of South Australia
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4. THE ATMOSPHERE

4.1DERIVATION OF THE EARTH'S ATMOSPHERE

4.1.1 THEORIES ON THE DERIVATION OF THE EARTH'S ATMOSPHERE

The derivation of the current Earth's atmosphere is inextricably linked with the origins of the Earth itself. Since the creation of Earth, which condensed out of dust from the Sun's nebula approximately 4.6 billion years ago, the Earth's atmosphere has undergone significant change from a relatively thin transient layer to the atmosphere of the current day – refer to Figure 1.

Figure 1 Comparison of the Earth's early climate (artist impression)[1] with today[2].

The Earth's paleoclimate is an active area of scientific research due to implications for the origin of life on Earth.

At the outset, it is important to understand that our knowledge of how the Earth has evolved, and hence how the atmosphere has been derived, is an active area of investigation in Science even today. Indeed, the early Earth's climate (paleoclimate) remains a contentious issue, with numerous divergent theories having been proposed ranging from glacial to hot climatic conditions[3]. These theoretical models are continually being refined and/or refuted as new research emerges.

Substantive research aimed at reconstructing the Earth's early climate has only been undertaken since the 1960's[4]. The catalyst for the boon in research into the 'deep time' preceding the Paleozoic era was a result of advancement in technologies, specifically isotopic analysis, and broader recognition of the importance of understanding the Earth's origins, specifically the origin of life on Earth.

The derivation of the Earth's atmosphere can be considered in four (4) main phases.

Based on current information, the atmosphere has broadly undergone at least four (4) main periods of change:

1) The Early Atmosphere – Hadean (4500 to 4000 Ma) to Early Archean (4000 – 3800 Ma)
2) The Second Atmosphere – Early Archean to Early Proterozoic (3800 to 2400 Ma)

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[1] P. Sawyer Smithsonian Institution Source: http://forces.si.edu/atmosphere/04_00_03.html

[2] NASA Earth Observatory January 22nd 2003 Source: https://earthobservatory.nasa.gov/images/80340/our-reach-should-exceed-our-grasp

[3] Krissansen-Totten J., Arney G.N. and Catling D.C. (2018) 'Constraining the climate and ocean pH of the early Earth with a geological carbon cycle model' PNAS (Proceedings of the National Academy of Sciences of the United States of America), April 17 2018, vol. 115, no.16, pp. 4105-4110. Source: http://www.pnas.org/

[4] Barry and Chorley 2010 'Atmosphere, Weather and Climate' Ninth Edition 2010 by Routledge, Oxon OX14 4RN England.

3) The Third Atmosphere – Early Proterozoic to Phanerozoic (2400 to 540 Ma)
4) The Current and Fourth Atmosphere – Phanerozoic to Current day (540 Ma to now)

Each of these periods will now be outlined, in terms of the key characteristics of the atmosphere, allied with the concurrent events in the biosphere, hydrosphere and geosphere, which have impacted on how the atmosphere evolved. It should be noted that the atmosphere and each of the other 'spheres' have a symbiotic relationship, where a change in one sphere has the potential to impact on the remaining spheres.

THE EARLY ATMOSPHERE – HADEAN TO EARLY ARCHEAN

The Earth's earliest atmosphere was very thin and was initially only composed of hydrogen (H_2) and helium (He) gases, which were quickly dispersed by the solar winds and vented into space. This very early atmosphere was subsequently replaced by an atmosphere formed from the accumulation of gases from the de-gassing associated with broad-scale volcanism present during the Hadean era – refer to Figure 2[5].

The primary gases present in Hadean-Early Archean atmosphere included: carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2), water vapor (H_2O) and compounds of nitrogen (N_2 and NH_3). There was no free oxygen present – a significant contrast to the present day.

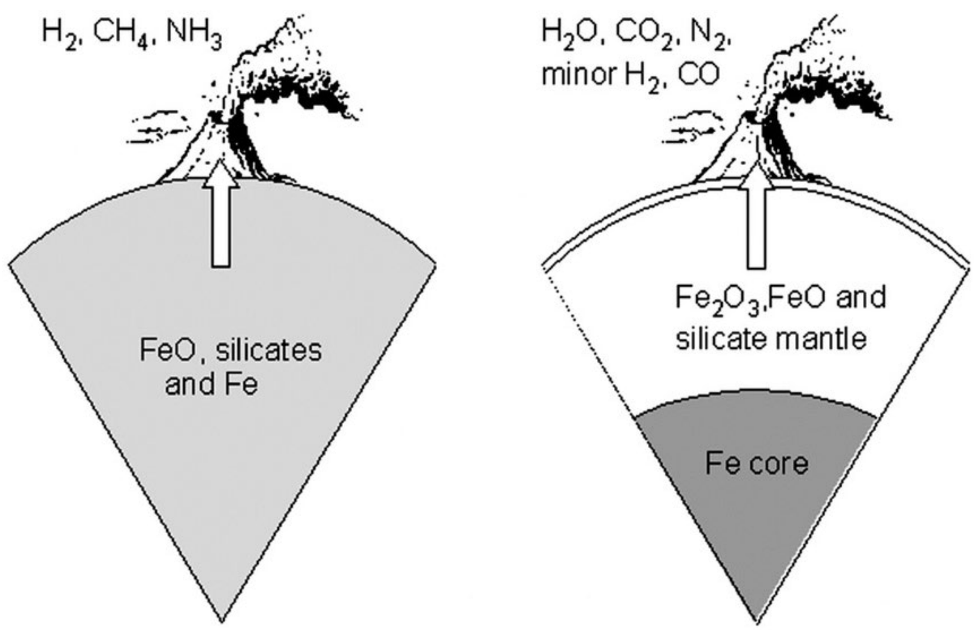

Figure 2 Volcanic de-gassing emits the gases present in the Earth's early atmosphere[6]: Left, early Earth prior to the formation of the Earth's core. Right, Earth after further differentiation and the formation of an inner core.

During this period the Sun's luminosity was relatively low - estimated to be at only 70% of current levels[7]. Despite this, it is proposed that the Earth's early atmosphere may have been a moderated by a 'greenhouse' effect, or at a minimum, been a temperate climate.

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[5] Source: http://www.columbia.edu/~vjd1/solar_nebula.htm

[6] Catling, D., & Kasting, J. (2017). *Evolution of the Earth's Atmosphere*. In Atmospheric Evolution on Inhabited and Lifeless Worlds (pp. 169-326). Cambridge: Cambridge University Press.

[7] Chyba C.F. (2010) 'Countering the Early Faint Sun' Science, vol. 328 (5983), pp. 1238-1239.

As early stage 4,400 Ma[8] a 'buoyant' crust may have been present whilst the Earth's interior consolidated into a denser core with overlying mantle. This process was accompanied by significant cooling and the formation of oceans – a significant driver in changing the atmospheric composition due to interaction with the hydrosphere.

It was also during this period that the Earth was subject to intensive comet and meteor impacts, ending 3,800 Ma – this is known as the **'late heavy meteorite bombardment' (LHB)**[8].

The boundary between the Earth's 'early' atmosphere and the 'second' atmosphere is marked by the emergence of anaerobic life forms ~3,800Ma.

In summary, the Earth's early atmosphere was most likely composed of compounds of hydrogen (H_2 and H_2O), nitrogen (N_2 and NH_3), sulfur (SO_2) and carbon (CH_4 and CO_2), with no free oxygen (O_2) being present. The overall climate is considered to have been temperate i.e. only slightly higher than today.

The boundary between the early and second atmosphere is marked by the emergence of anaerobic life forms in ~3,800 Ma.

SCIENCE AS HUMAN ENDEAVOUR – SCIENTIFIC INVESTIGATIONS INTO THE EARLY ATMOSPHERE

The following outlines some of the key contributions to our current understanding of the Earth's early atmosphere since the 1970's:

- In 1978, Hart[9] provided the first cohesive outline of the evolution of the Earth's early atmosphere. In Hart's model, the early atmosphere was dominated by carbon dioxide (CO_2), methane (CH_4) and compounds of nitrogen (NH_3 and N_2), with only minor contributions of other gases (e.g. hydrogen).
- Figure 3 presents the evidence for the composition of the Earth's atmosphere which was available at that time. Since then, there has been considerable changes to this original model. This was followed by the work of Kasting[10] (1993) whom proposed that the Earth formed within 10-100 My whereby the initially hot interior resulted in the formation of the Earth's core in tandem with the process of accretion.
- Once the main accretionary phases ceased, "*the surface heat flux would have dwindled, and the steam atmosphere would have rained out to form an ocean. The remaining atmosphere would probably have been dominated by carbon and nitrogen compounds, primarily CO_2, CO and N_2…Climate modelling indicates that the mean surface temperature … would have been ~85°C*"[10].
- As recently as April 2018, it has been proposed[3] that the prevailing surface temperature in the Archean was likely to be constrained to 0-50°C i.e. a temperate climate, neither glacial nor significantly hotter, and only slightly higher than current temperatures. This most recent work is significant because it is based on a "self-consistent" geological carbon model[11] that incorporates the latest understanding of ocean pH, takes into account lower solar luminosity in the Archean and other key parameters, such as seafloor and continental weathering.
- Finally, whilst the timing for the emergence of the first life form on Earth is yet to be fully resolved, it is considered that the first life form may have emerged as early as 4,300 Ma[12] or as late as 3,700 Ma[13]. For simplicity, the boundary may be set at 3,800 Ma.

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[8] Hessler A. M. (2011) 'Earth's Earliest Climate' By: Angela M. Hessler. Nature Education Knowledge 3(10):24.

[9] Hart M.H. (1978) 'The Evolution of the Atmosphere of the Earth' Icarus 33, pp23-39.

[10] Kasting J.F. (1993) 'Earth's Early Atmosphere' Science, vol. 259, 12 February 1993.

[11] Totten et al (2018) based their findings on a "self-consistent geological carbon model … On long timescales, both climate and ocean pH are controlled by the geological time scale" (Totten et al. 2018, p.4105-6).

[12] Source: https://www.livescience.com/57942-what-was-first-life-on-earth.html [Accessed: 7 October 2018]

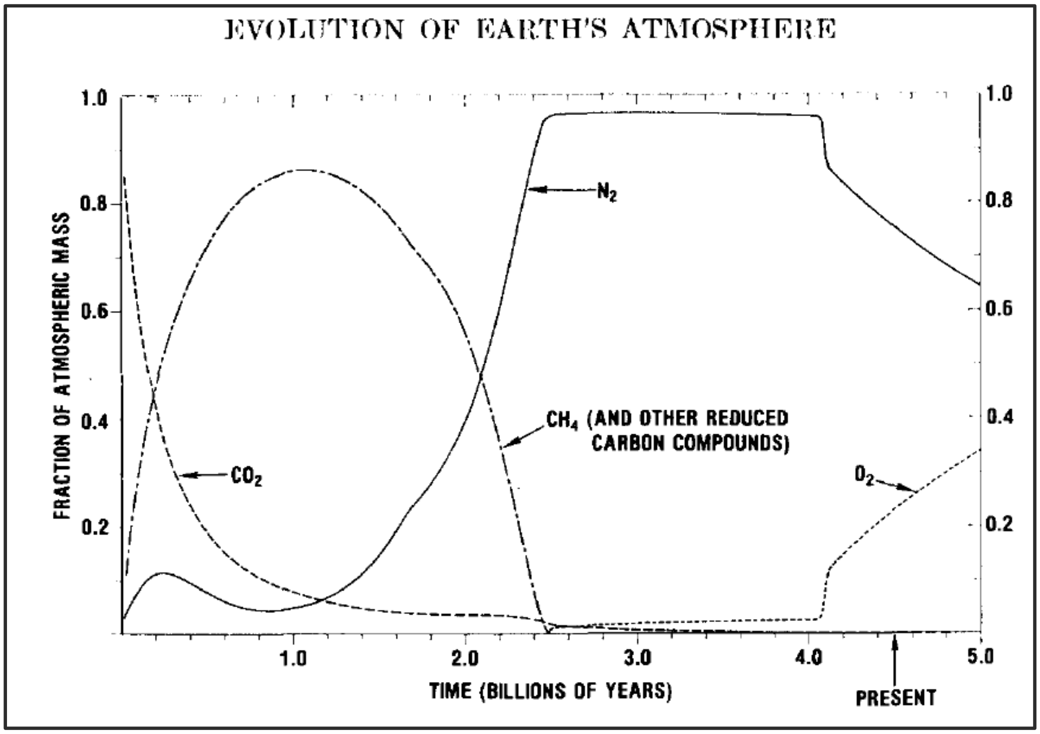

Figure 3 Hart's (1978) model for the evolution of the Earth's Atmosphere[9]

THE SECOND ATMOSPHERE – EARLY ARCHEAN TO EARLY PROTEROZOIC

The atmosphere during the Early Archean (3,800 Ma) to the Early Proterozoic (2,400 Ma) was characterized by the following:

- Emergence of **anaerobic** life forms ~3,700 – 4,000 Ma (if not earlier[14]). The latest timing for the emergence of life is set at 3,700 Ma[8]. This is an area of active ongoing research e.g. Keshefi and Lovely (2003) and Lin et al (2006) proposed that 'extremophiles'[15] may have been present prior to this time, and some authors purport dates as early as 4,300 Ma[12].
- These anaerobic bacteria and Archaea formed the pre-cursor for **photosynthetic bacteria** (Cyanobacteria) in ~3,000 Ma[16] - these bacteria were responsible for producing free O_2 for the first time.
- Whilst free O_2 began being produced as early as 3,000 Ma, it was only ~600 My later, in ~3,450 – 3,400 Ma when the presence of significant O_2 in the atmosphere occurred. This lag in time was due to the reaction of oxygen with iron (Fe^{2+}), and other reduced metal species present in the oceans.
    - Further details on the impact of the biosphere on the evolution of the atmosphere in Section 4.1.4.
  - During this period there was also an overall decrease in the hydrogen (H_2) gases present, allied with an increase in methane (CH_4), in a process known as **'methanogenesis'.** This led to a moderation of the CO_2 output from volcanic activity occurring at the time, and resulted in the deposition of carbonaceous sediments[28].
  - It is proposed that meteorite bombardment activity may have continued to as late as 3,000 Ma[17] - this is significant due to the potential to impact on any incipient life forms being present and its potential impact on the oceans.

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13 Knoll A.H. and Nowack M.A. (2017) 'The timetable of evolution' Science Advances, vol. 3 (5), e1603076.

14 This is an active area of scientific investigation, with new evidence emerging resulting in this timeline being continually refined.

15 'Extremophile: An organism that thrives in physically or geochemically extreme conditions' (Hessler 2011).

16 Blankenship R.E. (2017) *How Cyanobacteria went green*. Science Vol. 355 (6332) pp.1372-73.

The demarcation between the 'second' atmosphere and the 'third', is a result of a significant rise in O_2 concentration which occurred ~2,400 Ma after a tipping point was reached – where the amount of O_2 being produced via photosynthesis outstripped the amount of O_2 being utilized for oxidation. This event is known as the **'Great Oxidation Event' (GOE)** – refer to Figure 4.

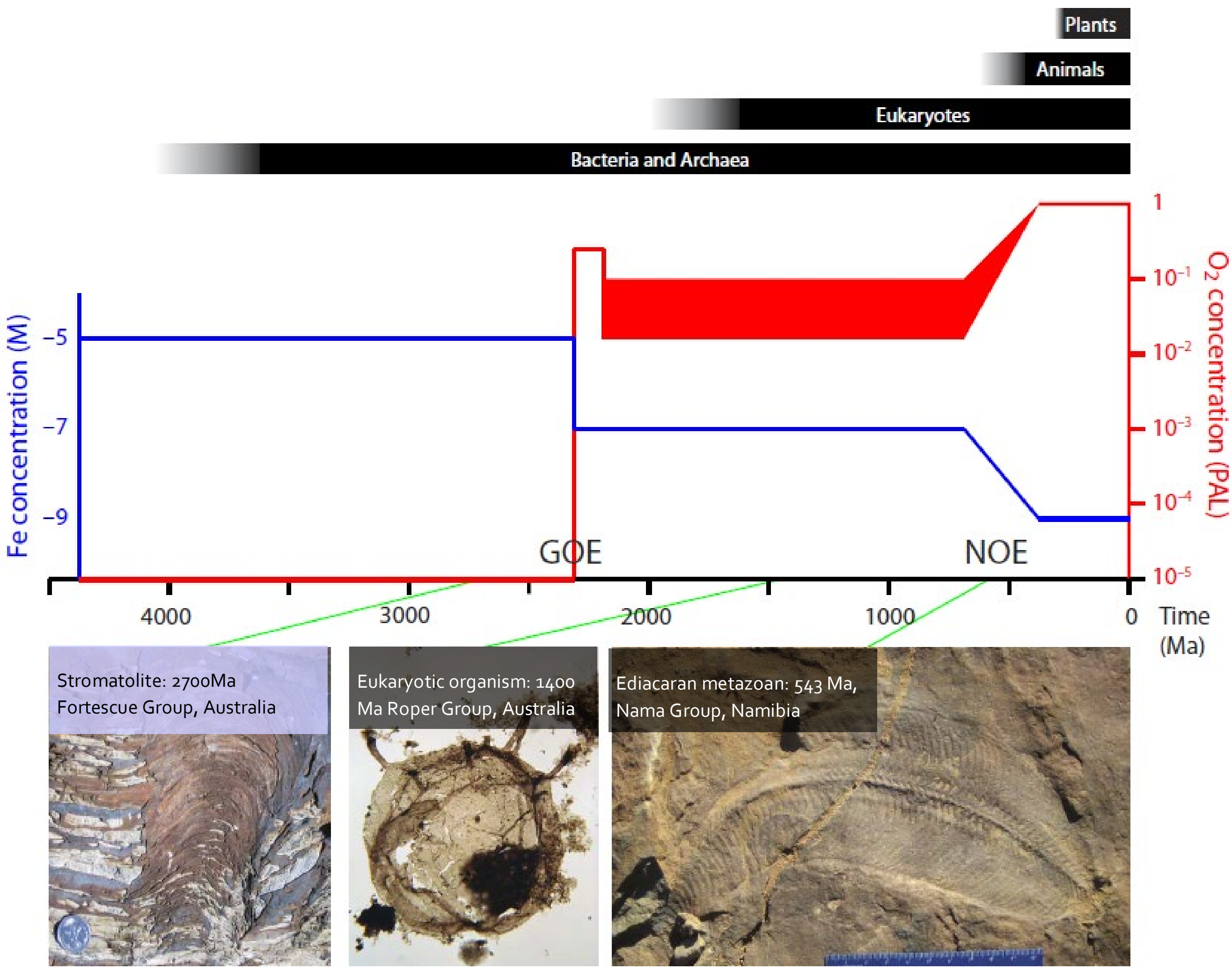

Figure 4: Timeline depicting the presence of O_2 in the atmosphere and Fe in seawater (Knoll and Nowack 2017)

The Earth's 'second' atmosphere emerged in tandem with the appearance of the earliest life-forms on Earth – archaea and anaerobic bacteria.

These life-forms altered the chemical make-up of the atmosphere by initially reducing the levels of H_2 and increasing levels of CH_4.

This was followed by the evolution of photosynthetic bacteria which began producing O_2. The availability of O_2 led to a moderation of the levels of CO_2 in the atmosphere, via 'the carbon cycle' and was also utilized to oxidize reduced metal species present in the oceans. After a lag of ~600 My, a tipping point was reached where O_2 levels began to rise in the atmosphere – the Great Oxidation Event (GOE) in ~2,400 Ma.

During this period, meteorite bombardment may have continued up until ~3,000 Ma.

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[17] Source: https://www.newscientist.com/article/dn26055-earths-early-life-endured-long-asteroid-bombardment/ [Accessed: 10 October 2018]

THE THIRD ATMOSPHERE – EARLY PROTEROZOIC TO END OF NEOPROTEROZOIC

The atmosphere during the Early Proterozoic (2,400 Ma) to the end of the Neoproterozoic (550 Ma) was characterized by:

- The first major oxygenation event in 2400 Bya – otherwise known as the **Great Oxygenation Event (GOE)**[13] which resulted in O_2 levels rising from essentially zero to one 1-10% of current levels. As noted previously, the presence of O_2 is attributed to photosynthetic bacteria which evolved ~600 My previously.
- The formation of **Banded Iron Formations (BIF)** provide evidence of the availability of abundant O_2 during this period, which resulted in the deposition of large scale iron-enriched rock formations up until ~1,800 Ma[18]. Formation of BIFs ceased after this period as all available iron had been deposited in the ocean basins, with no further iron being available for deposition.
- The period from ~1,800 to ~700 Ma was a period of relative stability in terms of the atmospheric composition.
- At ~700 Ma the atmosphere was again impacted by changes in the biosphere, with the emergence of multi-cellular life forms[28]. The occurrence of these multi-cellular life forms was coincident with the formation of an effective ozone layer being formed within the stratosphere.

The demarcation between the 'third' atmosphere and the 'fourth', is a result of a second rise in the O_2 levels in the atmosphere – known as the **Neoproterozoic Oxygenation Event (NOE)** - refer to Figure 4.

The Earth's 'third' atmosphere was a period of relative stability characterized by the rise in O_2 levels allied with the formation of banded iron formations (BIF).

A second rise in oxygen levels at the end of the Neoproterozoic – the Neoproterozoic Oxygenation Event (NOE) - marked the transition to an atmosphere similar to the current day.

THE FOURTH ATMOSPHERE – END OF THE NEOPROTEROZOIC TO CURRENT DAY

The atmosphere transitioned into the 'fourth' atmosphere at the end of the Neoproterozoic due to a second major oxygenation event in 550-500 Ma – otherwise known as the Neoproterozoic Oxygenation Event (NOE)[13]. This 'fourth' atmosphere has transitioned into the current atmosphere which is predominantly composed of nitrogen (N_2) and oxygen, with <1% of other trace gases.

Further details on the current atmosphere – composition and structure – is outlined in Section 4.2.

The Earth's 'fourth' atmosphere realized the atmospheric conditions similar to the current day and commence 550-500 Ma.

SCIENCE AS HUMAN ENDEAVOUR - WHAT HAS ARGON GOT TO DO WITH IT?

"The elemental abundance and isotopic composition of noble gases in the atmosphere inform us about the Earth's composition, the history of the ocean and the atmosphere, and the present and past geodynamic of the planet." In particular, "the atmospheric abundance of ^{40}Ar reflects the balance between production by radioactive decay of ^{40}K in the crust, upper mantle and lower mantle, and the outgassing of the atmosphere"[19].

[18] Catling D.C. and Claire M.W. (2005) *How Earth's atmosphere evolved to an oxic state: a status report*. Earth and Planetary Science Letters 237 (2005) pp. 1-20.

[19] Bender M.L., Barnett B., Dreyfuss G., Jouzel J. and Porcelli D. (2008) 'The contemporary degassing rate of 40Ar from the solid Earth' PNAS vol. 105 no. 24, p.8232, June 17 2008.

- Argon (Ar) is a colorless and odorless 'noble'[20] gas. Ar is the third-most prevalent gas in the Earth's atmosphere, after nitrogen and oxygen, accounting for ~1%[21] of all of atmospheric gases[22].
- The presence of Ar in the atmosphere was first proposed by Henry Cavendish in 1785, however its presence was only confirmed >100 years later, when Lord Raleigh and Prof. Ramsay published their research in journal articles between 1894 and 1897[23] – '*Argon, a new constituent of the atmosphere*'.
- Argon has a number of isotopes (including the stable isotopes: ^{36}Ar, ^{38}Ar, and ^{40}Ar), however of primary isotope of interest to Earth scientists is ^{40}Ar.
- The proportion of ^{40}Ar is so useful because it is a radiogenic isotope and it "*reflects the balance between the production of radioactive decay of ^{40}K in the crust, upper mantle and lower mantle, and outgassing to the atmosphere…with a ^{40}Ar outgassing rate of 1.1 ± 0.1 x 10^8 mol/yr*"[19].
- In contrast, the remaining two Argon isotopes (^{36}Ar and ^{38}Ar) have remained relatively stable over geological time.
- As a consequence of ^{40}Ar radiogenic origins, K-Ar dating has become one of the key techniques used to date the ages of rocks formed during the Earth's history – as outlined in Figure 5:.

Potassium-argon dating, method of determining the time of origin of rocks by measuring the ratio of radioactive argon to radioactive potassium in the rock. This dating method is based upon the decay of radioactive potassium-40 to radioactive argon-40 in minerals and rocks; potassium-40 also decays to calcium-40. Thus, the ratio of argon-40 and potassium-40 and radiogenic calcium-40 to potassium-40 in a mineral or rock is a measure of the age of the sample. The calcium-potassium age method is seldom used, however, because of the great abundance of nonradiogenic calcium in minerals or rocks, which masks the presence of radiogenic calcium. On the other hand, the abundance of argon in the Earth is relatively small because of its escape to the atmosphere during processes associated with volcanism.

The potassium-argon dating method has been used to measure a wide variety of ages. The potassium-argon age of some meteorites is as old as 4,500,000,000 years, and volcanic rocks as young as 20,000 years old have been measured by this method.

Figure 5 Outline of K-Ar Dating (Source: Encyclopedia Britannica)[24] [25]

4.1.2 ATMOSPHERIC COMPOSITION – THEN AND NOW

To summarize, the Earth's atmosphere has evolved significantly since the Hadean and Archean eons:

> *"Perhaps what is most telling is that climate regulation has been a mainstay from the beginning. Despite large changes in solar energy as well as dramatic impact events, our climate has been perpetually suitable for some form of life. Inorganic processes have played a large part in this regulation, particularly through cycles of outgassing, weathering, albedo, and oceanic circulation associated with plate tectonics…*

[20] 'Noble' gases are non-reactive i.e. not readily chemically reactive; they may also be known as 'inert' gases.

[21] Source: http://www.rsc.org/periodic-table/element/18/argon [Accessed: 4 November 2018]

[22] Source: https://www.lenntech.com/periodic/elements/ar.htm [Accessed: 4 November 2018]

[23] W.W.R. (1897) '*Argon, a new constituent of the atmosphere*' Science 6 (150), p. 743

[24] Source: https://www.britannica.com/science/potassium-argon-dating [Accessed: 4 November 2018]

[25] Source: http://periodictable.com/Elements/018/ [Accessed: 4 November 2018].

However, we can also see that when conditions reach a tipping point (e.g. the GOE), change can be extraordinarily rapid and (as yet) irreversible. As we continue to impact the ocean-atmosphere system, we must look to deep-time climate change – particularly these abrupt and seemingly permanent transitions – to more fully frame our forecasts and design our solutions"[26].

The key changes in the Earth's atmosphere are outlined in Figure 6.

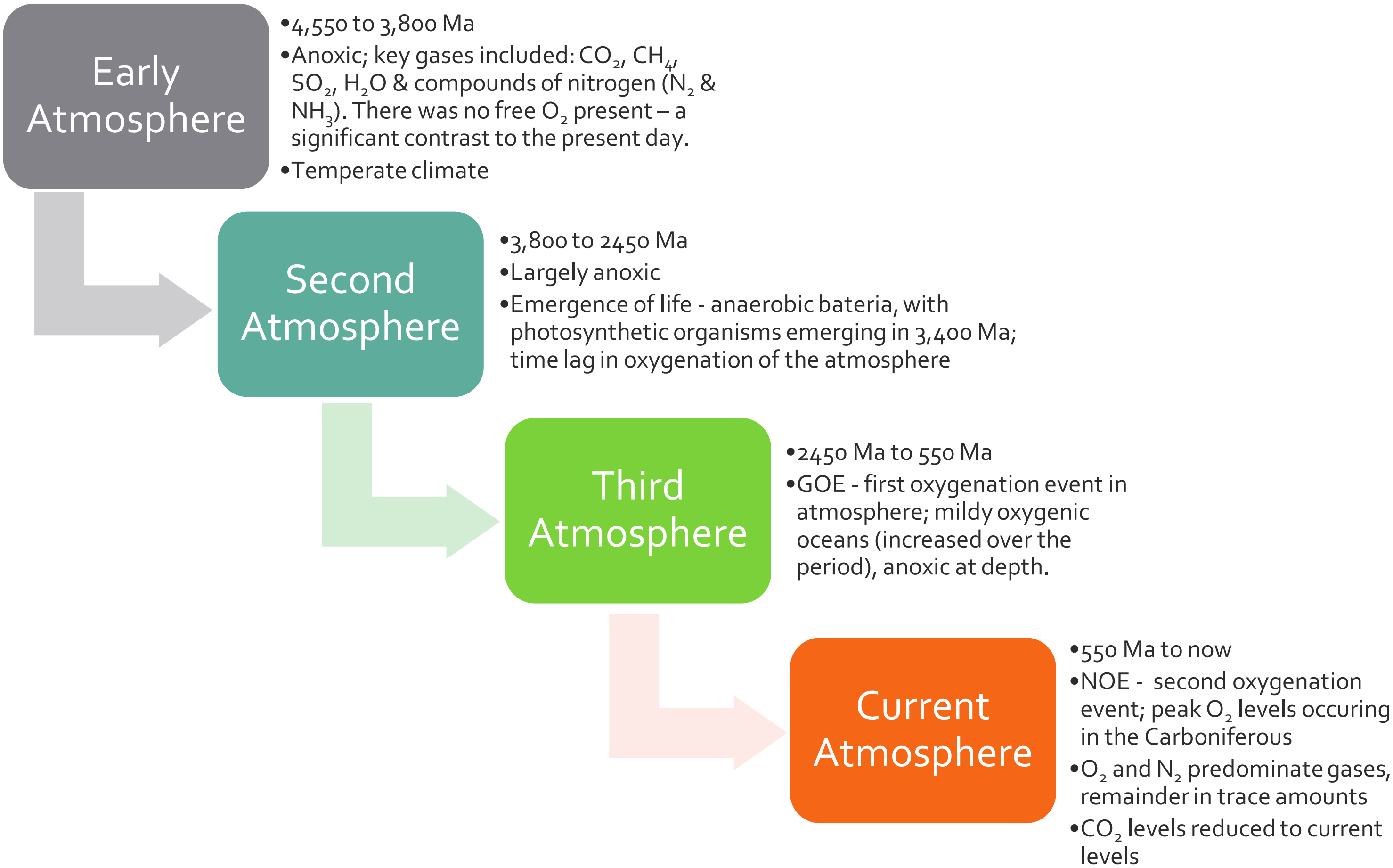

Figure 6 Key Steps in the Formation of the Current Atmosphere[27] (based on Holland 2006).

The levels of free oxygen and the amount of carbon dioxide present in the atmosphere are two of the key gas signatures for defining the four (4) staged changes in the atmosphere from the Hadean to the current day, as graphically illustrated in Figure 7 and Figure 8.

[26] Hessler (2011) p. 7/11

[27] Holland (2006) *The oxygenation of the atmosphere and oceans*. Phil. Trans. R. Soc. B (2006), Vol. 361, 903-915.

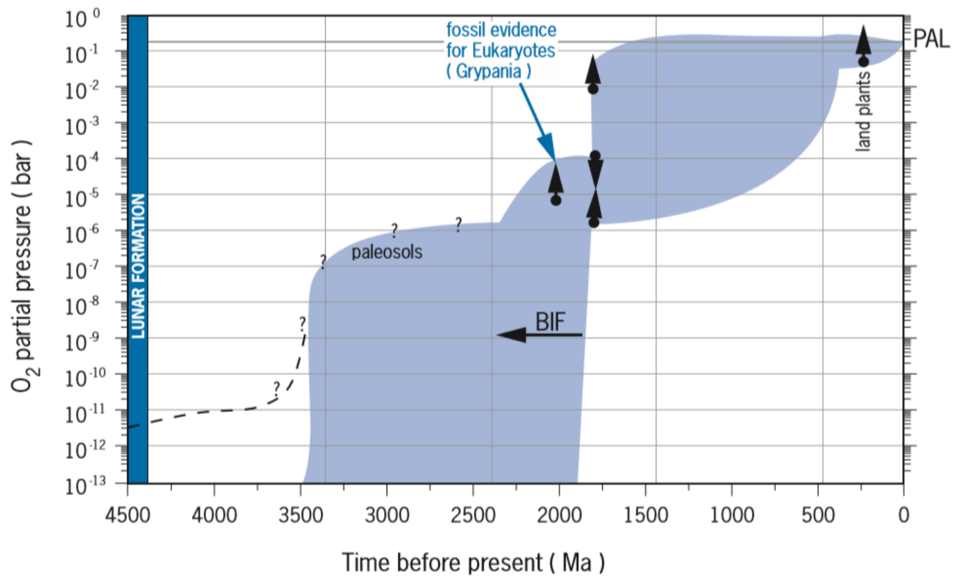

Figure 7 Partial Pressure in O_2 in the Atmosphere Over Time[28]

Figure 7 depicts the rise in free oxygen within the Earth's atmosphere, from essentially zero, prior to 3,500 Ma to current levels. As is evident, oxygen only began to accumulate to significant levels after ~2,450 Ma (the GOE), where it then remained stable until a renewed rise after ~550 Ma (the NOE). The low levels of oxygen present prior to 2,450 Ma were utilized to moderate the proportions of CO_2 present within the atmosphere at the time, and also to aid the oxidation of various metal ion species present within the Earth's oceans (e.g. Fe).

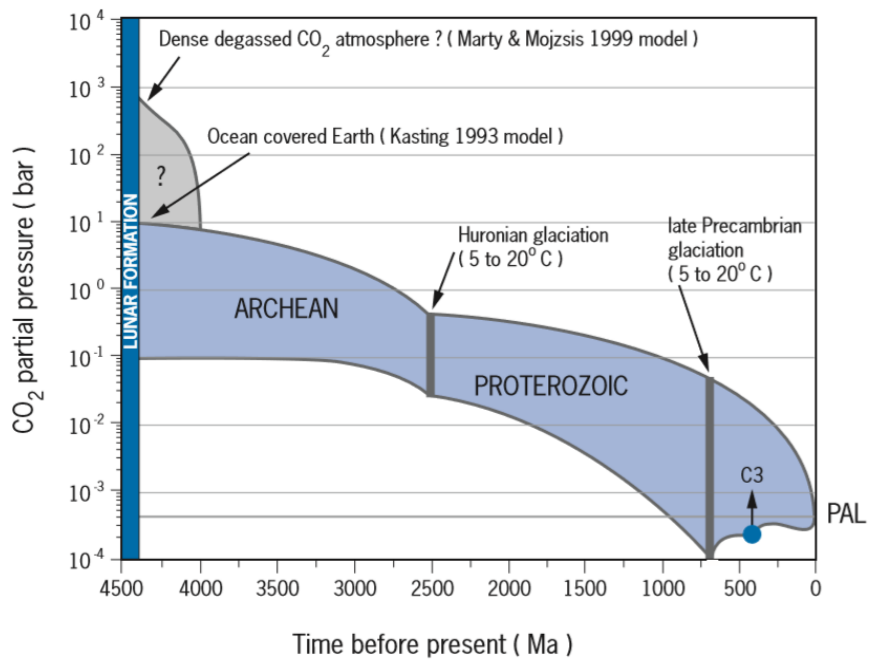

Figure 8 Partial Pressure in CO_2 in the Atmosphere Over Time[28]

Figure 8 depicts the change in CO_2 since the Earth's formation, including key glaciation events overlaid over the timeline for the oxygenation of atmosphere, the GOE and the NOE.

[28] Source: http://www.esalq.usp.br/lepse/imgs/conteudo_thumb/Life-and-the-Evolution-of-earths-atmosphere-2.pdf [Accessed: 9 October 2018]

4.1.3 NITROGEN IN THE ATMOSPHERE – ESSENTIAL FOR LIFE

Nitrogen (N_2) is the most abundant gas occurring with the current atmosphere at ~78% by volume, and has been present, in varying proportions since the very earliest stages of Earth's existence.

Atmospheric N_2 is very stable arising from its molecular form, being composed of two atoms of nitrogen bonded to each other in a triple covalent bond. This molecular form necessitates a large amount of energy to be used to break this triple bond.

The process of removing nitrogen, in the form of N_2, from the atmosphere is termed 'fixation', and this happens via two natural pathways (refer to Figure 9) within a geochemical cycle known as the 'Nitrogen Cycle':

- Pathway (1) Atmospheric Fixation (via lightning) and
- Pathway (2) Biological Fixation (via nitrogen-fixing bacteria)

The fixation process converts nitrogen (N_2) into nitric oxide (NO) via pathway 1 and ammonia (NH_3) via pathway 2. After the release of nitrogen via these two pathways, these molecules are then further converted into proteins, nitrous oxide (N_2O) and nitrates (NO_3^-) – forms readily useful to living organisms. The nitrogen is thereby available in various forms and processes, before eventually being recycled and returned into the atmosphere – hence the term 'Nitrogen Cycle'.

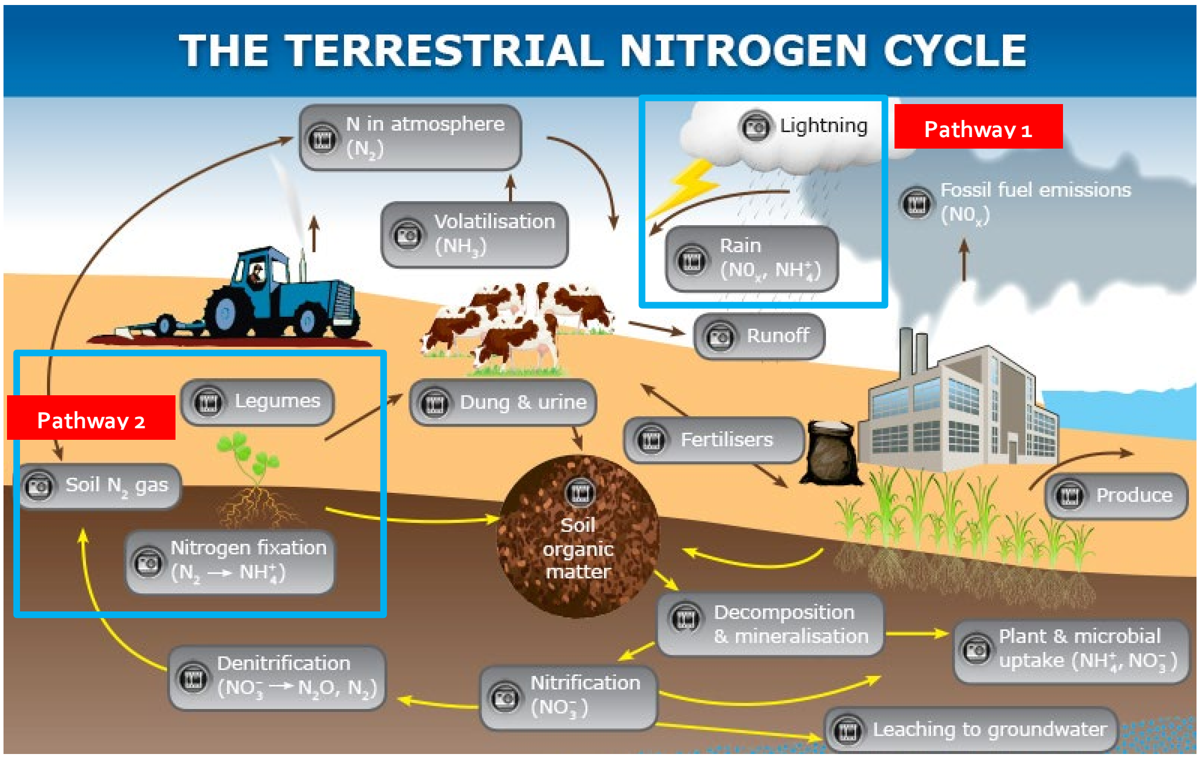

Figure 9 Simplified nitrogen cycle[29]

Nitrogen is essential to all living organisms. It is used in the formation of proteins such as amino and nucleic acids, as well as other key functions. In addition, nitrogen is a *"major component of chlorophyll, the compound by which plants use sunlight energy to produce sugars from water and carbon dioxide (i.e., photosynthesis)"[30].*

[29] Source: https://www.sciencelearn.org.nz/image_maps/14-the-terrestrial-nitrogen-cycle [Accessed: 10 November 2018]

[30] Source: https://www.cropnutrition.com/efu-nitrogen [Accessed: 10 November 2018]

As Figure 9 illustrates, access for living organisms, such as plants and animals, is primarily made possible via the action of these two natural pathways (1 and 2) identified above[31]. It is not possible for plants and animals to synthesize the nitrogen needed directly from the atmosphere, despite is ready availability, because it is not present in a form that is able to be integrated and/or metabolized.

The Nitrogen Cycle acts in concert with other biogeochemical cycles (e.g. the Carbon Cycle, the Phosphorus Cycle, the Sulphur Cycle and the Water Cycle) to regulate and convert the elements needed for growth and sustainability for living organisms throughout the Earth.

> Author's update: There has been recent research published in 2018 [32]which has proposed a modification to the conventional view that fixation of nitrogen primarily occurs from atmospheric N_2 sources. This research suggests that significant nitrogen is released via weathering, particularly in montane and high latitude biomes, which provide a substantial source of nitrogen to be converted via standard plant pathways.
>
> This research has implications for the carbon and other biogeochemical cycles; and may have broader implications for climate change science.

Figure 10 Pathways for N_2 fixation – Pathway 1 Biological Fixation (Photograph 1: Nitrogen-fixing bacteria[33], often co-existing with legume plants), and Pathway 2 Atmospheric Fixation (Photograph 2: Lightning)[34]

Further discussion on the 'Nitrogen Cycle'[35] will be addressed in Topic 6: The Biosphere.

Further discussion on 'The Evolution and Future of Earth's Nitrogen Cycle' is available in an article included in Science[36].

Nitrogen (N_2) is readily available in the Earth's atmosphere, however requires conversion from molecular N_2 to other forms, to enable nitrogen to utilized in biological processes. This is known as the 'Nitrogen Cycle'.

Nitrogen is essential for living organisms because it forms the basis of key proteins (e.g. amino acids) and facilitates growth.

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[31] An alternate process for fixing N_2 from the atmosphere is via the industrial process known as the Haber process, which produces ammonia based fertilizers on an industrial scale; this is not part of the 'natural' nitrogen cycle per se.

[32] Houlton B. Z. , Morford S.L. and Dahlgren R.A. (2018) '*Convergent evidence for widespread rock nitrogen sources in the Earth's surface environment*' Science 360 (6834), pp. 58-62.

[33] http://www.soilquality.org.au/factsheets/legumes-and-nitrogen-fixation-south-australia [Accessed: 10 November 2018]

[34] https://www.agupdate.com/agriview/lifestyles/ask-the-weather-guys/article_dd7a80a6-4745-524d-bd08-bf3573c77e8e.html [Accessed: 10 November 2018]

[35] For more information on the nitrogen cycle, including details on each of the key steps, a suggested reference is as follows: Bioninja (2018) Source: http://ib.bioninja.com.au/options/option-c-ecology-and-conser/c6-nitrogen-and-phosphorus/nitrogen-cycle.html

[36] Canfield D.E., Glazer A.N. and Falkowski P.G. (2010) 'The Evolution and Future of Earth's Nitrogen Cycle' Science Vol. 330 (6000), pp. 192-196, 8 October 2010. Source: www.sciencemag.org

4.1.4 SYMBIOTIC RELATIONSHIP OF THE BIOSPHERE AND THE ATMOSPHERE – THIS RISE OF OXYGEN

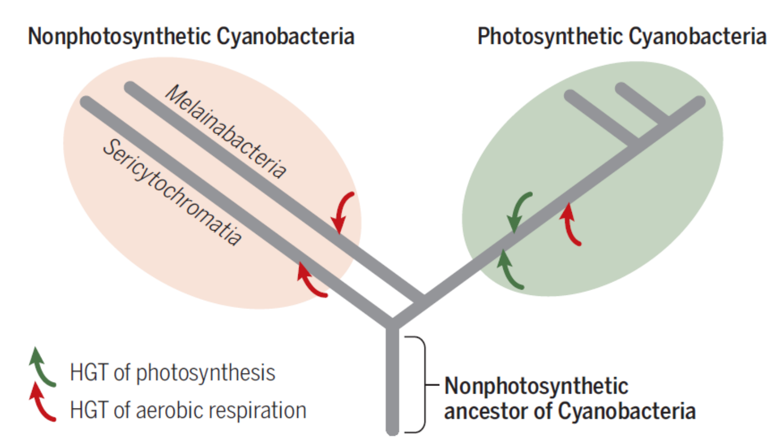
The first key milestone in the Earth's biological history is the appearance of the first life form(s) on Earth, which may have emerged as early as 4,300 Ma[12] or as late as 3,700 Ma[13]. Evidence for these early carbon-based life forms are preserved in sedimentary rocks dated for this period. These early life forms then evolved within the prevailing anaerobic atmospheric environment coincident with the onset of two key biogeochemical cycles: the Carbon and the Sulfur Cycles.

The second key milestone in Earth's biological history was the evolution and 'proliferation' of photosynthetic organisms – known as photosynthetic Cyanobacteria. These photosynthetic Cyanobacteria resulted in the rise of free oxygen within the Earth's atmosphere.

The emergence of **photosynthetic bacteria (Cyanobacteria)** was a key turning point in the evolution of the Earth's atmosphere and caused the atmosphere to change from anaerobic to aerobic conditions. This turning point is known as the Great Oxidation Event (GOE) and is widely agreed to have occurred at ~2,450 to 2,400 Ma.

A point of contention remains however, where scientists disagree on exactly how the GOE was initiated. For example, was the GOE was an irreversible change which occurred over a very short period of time, or were there periods where the levels of oxygen in the atmosphere fluctuated between anaerobic and aerobic conditions, potentially over a 600 My time frame[16]. It is proposed that the timing of the GOE may have been delayed due to the requirement to oxidize reduced metal species occurring within Earth's oceans (refer also to Section 4.1).

These **photosynthetic Cyanobacteria** evolved from a non-photosynthetic ancestor, and both non-photosynthetic and photosynthetic organisms co-existed – refer to Figure 11. The emergence of these photosynthetic life-forms has ultimately led to the evolution of the complex multi-cellular life forms present on Earth today[37].



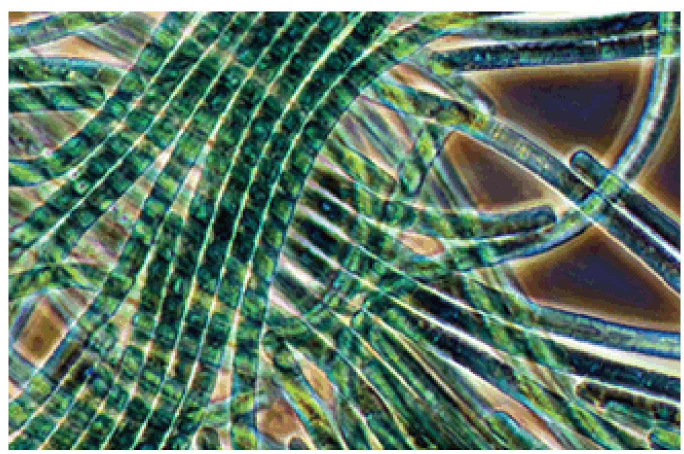


Figure 11 Evolution of photosynthetic Cyanobacteria ("How Cyanobacteria went green"[16]). Note – HGT = horizontal gene transfer.

The increasing presence of oxygen within the Earth's atmosphere led to a decline in the abundance of primeval anaerobic organisms due their inability to adapt oxygenic conditions, and ultimately restricting their occurrence to organic-rich muds and deep-water sediments, where they still occur today[38].

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[37] Soo R. M., Hemp J., Parks D. H., Fischer W. W. and Hugenholtz P. (2017) *'On the origins of oxygenic photosynthesis and aerobic respiration in Cyanobacteria'* Science Vol. 355, pp. 1436-1440, 31 March 2017.

[38] Mojzsis S.J. (2018) 'Life and the Evolution of the Earth's Atmosphere. Source: https://www.amnh.org/learn/pd/earth/pdf/evolution_earth_atmosphere.pdf [Accessed: 10 November 2018]

The interplay between the composition of the Earth's atmosphere and the emergence of life clearly demonstrates the inter-dependence of each of the Earth's four spheres - the atmosphere, the biosphere, the hydrosphere and the geosphere.

An overall timeline showing the evolution of life on Earth is presented in Figure 12. Further discussion on the evolution of life and the Earth's key biogeochemical cycles (e.g. the Carbon Cycle) will be addressed in Topic 6: The Biosphere.

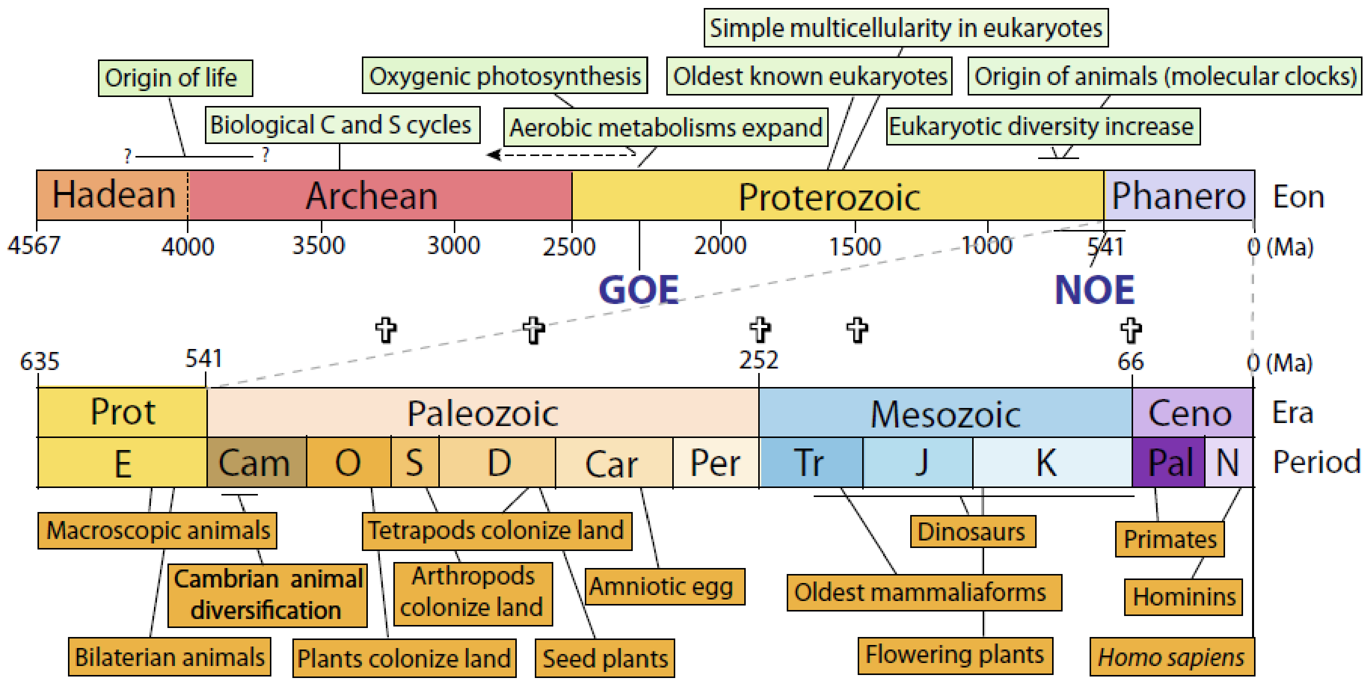

Figure 12: Timetable for the Evolution (Knoll and Nowack 2017). Note: the crosses indicate times of mass extinctions.

KEY LEARNING OUTCOMES (SACE 2018)

From the 'Subject Outline' developed by SACE (2018)[39], the following are the key learning outcomes:

		Check
4.1	**Derivation of the Earth's Atmosphere**	
4.1.1	Different theories exist that describe how the Earth's atmosphere was derived. Discuss theories, such as volcanic outgassing, about the derivation of the Earth's atmosphere.	☐
4.1.2	Compare the approximate proportion of nitrogen, oxygen, argon, and carbon dioxide in the Earth's atmosphere at different times in its history.	☐
4.1.3	Explain why nitrogen is essential for life.	☐
4.1.4	The composition of the Earth's atmosphere has been significantly modified by photosynthesizing organisms. Describe fluctuations in the proportion of oxygen in the Earth's atmosphere over geological time.	☐

[39] Source: https://www.sace.sa.edu.au/web/earth-and-environmental-science/stage-1/planning-to-teach/subject-outline [Accessed: 23 August 2018]

QUESTIONS

Question 1 (2 marks)

Briefly outline key characteristics of the Earth's earliest atmosphere.

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Question 2 (4 marks)

Compare and contrast how the Earth's current atmosphere differs from the atmosphere at Earth's inception.

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Question 3 (4 marks)

Scientific understanding of the evolution of the Earth's atmosphere is continutally being updated and refined. Explain, with reason(s), why it is important for scientists to improve understanding of the derivation of the Earth's atmosphere.

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Question 4 (4 marks)

Clarify, with a diagram, the term 'outgassing' and why it is considered important in the evolution of the Earth's atmosphere.

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Question 5 (2 marks)

Define the term the 'Great Oxygenation Event' (GOE) and 'Neoproterozoic Oxygenation Event' (NOE).

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Question 6 (4 marks)

Explain the role of photosynthetic bacteria in changing the composition of the Earth's atmosphere.

Question 7 (2 marks)

Identify possible reason(s) for the delay in free oxygen within the Earth's atmosphere.

Question 8 (4 marks)

Outline the importance of nitrogen (N_2) the onset of life on Earth.

Question 9 (8 marks)

Identify, with the aid of a diagram, the key milestones in the development of the Earth's atmosphere *(Hint: refer to Figure 6)* from Hadean times to present.

Question 10 – Extension (4 marks)

Read the following article regarding the evolution

Venus may have hosted life, researchers say

Today it's an inferno, but scientists suggest billions of years ago the planet was cool enough to have liquid water. Richard A Lovett reports.

Source: https://cosmosmagazine.com/space/venus-may-have-hosted-life-researchers-say [Accessed: 10 November 2011]
https://cosmosmagazine.com/contributors/richard-a-lovett

The planet Venus may once have been hospitable to life, scientists say — possibly even more so than the early Earth.

Furthermore, this may have occurred even though Venus never had plate tectonics, the process by which the Earth constantly recycles its crust by bringing fresh material to the surface via volcanoes, while subducting old rock back into the interior in places such as deep-sea trenches. It's a process that produces damaging earthquakes and volcanoes, but also helps buffer our atmosphere's level of carbon dioxide, thereby keeping our surface temperature in the right range for liquid water.

"Plate tectonics is often tied to habitability, because Earth is habitable and has plate tectonics," says Matthew Weller, a planetary scientist at the University of Texas at Austin, US, who presented his recent paper at the Lunar and Planetary Science Conference (LPSC) in The Woodlands, Texas.

But, he says, that's not necessarily required: "Our work shows that a planet such as Venus, without plate tectonics, could have had surface temperatures over several billion years allowing for liquid water, which could allow for life."

The fact that Venus didn't have Earth-type tectonics doesn't mean its crust was totally stagnant. Rather, Weller says, it may have gone through "episodic" tectonics, in which it alternated between periods of extreme quiescence and ones of large-scale activity, like "plate tectonics on steroids."

The active periods, Weller says, produced enough carbon dioxide to warm the surface enough for life, even early in the solar system's history, when the Sun was 30% dimmer. At that time, the Earth may have been going through ice ages so extreme the period is often referred to as "Snowball Earth." But on Venus, enough carbon dioxide could have been released from the episodic upheavals to keep the planet pleasantly warm… and wet.

Eventually, the sun warmed, and the carbon dioxide built up too much. The water disappeared and Venus turned into the inferno it is today. But, notes Weller, “a few billion years ago, Venus might have been a warm, water world.”

Furthermore, he adds, many geophysicists believe that Earth, like Venus, started out with no plate tectonics (a situation in which its crust is described as a “stagnant lid”). This was followed by a period of episodic tectonics, like those that suggested for Venus, before our planet moved to its present regime of steady-state, continuous tectonics.

In the future, as our planet’s interior cools, Weller says, the reverse will happen, first with a return to episodic tectonics, then to a stagnant lid.

Studying Venus is therefore useful to understanding our own planet’s long-term future. “Where Venus is now is where the Earth will be a billion or so years from now,” Weller says.

Not that we need worry too much about our planet’s ultimate demise. But the discovery that Venus may once have been habitable is useful for exoplanet hunters hoping to find habitable worlds circling distant stars. Not only does it mean that planets in orbits comparable to that of Venus are not necessarily uninhabitable hothouses, but, Weller says, it means that “our solar system could have had three habitable planets early in its development.”

And if that happened here, he says, “many planets could have the potential for liquid water (and life).”

a) The author, Richard Lovett, asserts that the atmosphere and climate on Venus may have been able to support life.

What key idea(s) are presented.

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b) What are the implications for Earth based on the article?

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c) In your opinion, do you consider it useful to compare the atmosphere of the Earth to that of other planets, such as Venus or Jupiter.

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ACTIVITIES

- Investigate recent research that identifies the source of the Earth's nitrogen during the early history of its development.
- Investigate the gases that are typically released during modern volcanic activity, and the range of their relative proportions.
- Investigate the critical importance of Cyanobacteria found in stromatolites to oxygen production in the atmosphere and to the evolution of life on Earth.
- Watch *Crude - the Incredible Journey of Oil, at:* www.abc.net.au/science/crude/
- Compare the effects on past periods of a carbon rich atmosphere with the current levels of atmospheric carbon

KEY TERMS

Atmosphere, Hadean, Archean, Proterozoic, 'Great Oxygenation Event' (GOE), 'Neoproterozoic Oxygenation Event' (NOE), late heavy meteorite bombardment' (LHB), de-gassing, out-gassing, photosynthesis, Cyanobacteria, Archaea, aeraobic, anaerobic.

4. THE ATMOSPHERE

4.2 THE MODERN ATMOSPHERE

The modern atmosphere is a protective 'blanket'[1] of gases which filters the radiation from the Sun and acts to maintain the Earth's climate over the longer term. This mixture of gases is commonly referred to as air.

4.2.1 COMPOSITION OF THE EARTH'S ATMOSPHERE

Air is a mixture of gases with a composition of more than 99% nitrogen and oxygen, by volume, and is relatively consistent up to 80 km above the Earth's surface (exceptions being ozone and water vapour) - refer to Table 1[2]. Whilst nitrogen and oxygen are volumetrically significant, they do not impact significantly on the Earth's climate, rather this role is played by the trace gases, including the so-called "greenhouse gases".

Air is a mixture composed primarily composed of nitrogen and oxygen (>99% by volume), with only a minor contribution volumetrically, from the trace gases.

Table 1: Average composition of the dry atmosphere below 25km (based on Barry and Chorley 2010, p. 13).

Component	Symbol	Volume % (dry air)
Nitrogen	N_2	78.08
Oxygen	O_2	20.95
Argon	Ar	0.93
Carbon Dioxide	CO_2	0.037
Neon	Ne	0.0018
Helium	He	0.0005
Ozone	O_3	0.00006
Hydrogen	H_2	0.00005
Krypton	Kr	0.00011
Xenon	Xe	0.00009
Methane	CH_4	0.00017

"Greenhouse gases" (GHG) are gases which trap re-radiated solar heat within the atmosphere[3] and include: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and fluorinated gases (F-gases). Water is also a greenhouse gas, however it not typically included in discussions on GHG, because its occurrence is variable and intertwined with the 'global hydrological cycle'[2]. GHG will be discussed in more detail in Section 4.4.

Greenhouse gases play a key role in determining the temperature of the Earth's atmosphere.

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[1] Thompkins D.E. and Watkins J.M (2016) '*Exploring Earth and Environmental Science Year 11*', 2nd Edition, Earth Science Western Australia, Perth W.A.

[2] Barry R.G. and Chorley R.J. (2010) *Atmosphere, Weather and Climate*, Ninth Edition, Routledge, OXON OX14 4RN, England.

[3] EPA (2018) Overview of Greenhouse Gases, Environmental Protection Agency, U.S.A. Last updated on April 11, 2018 https://www.epa.gov/ghgemissions/overview-greenhouse-gases. Sourced: 11 September 2018

The composition of the Earth's modern atmosphere varies with height, latitude and season; it has also changed over time[2].

4.2.2 STRUCTURE OF THE EARTH'S ATMOSPHERE

The structure of the Earth's atmosphere can be separated into four main layers based on the changes in the temperature profile[2] – these are, in order of rising height from the Earth's surface:

1. Troposphere
2. Stratosphere
3. Mesosphere
4. Thermosphere

Figure 1 depicts these four main layers in the atmosphere. At the outer limits of the thermosphere, the atmosphere transitions into the exosphere[4].

Density of gases and pressure decreases with altitude.

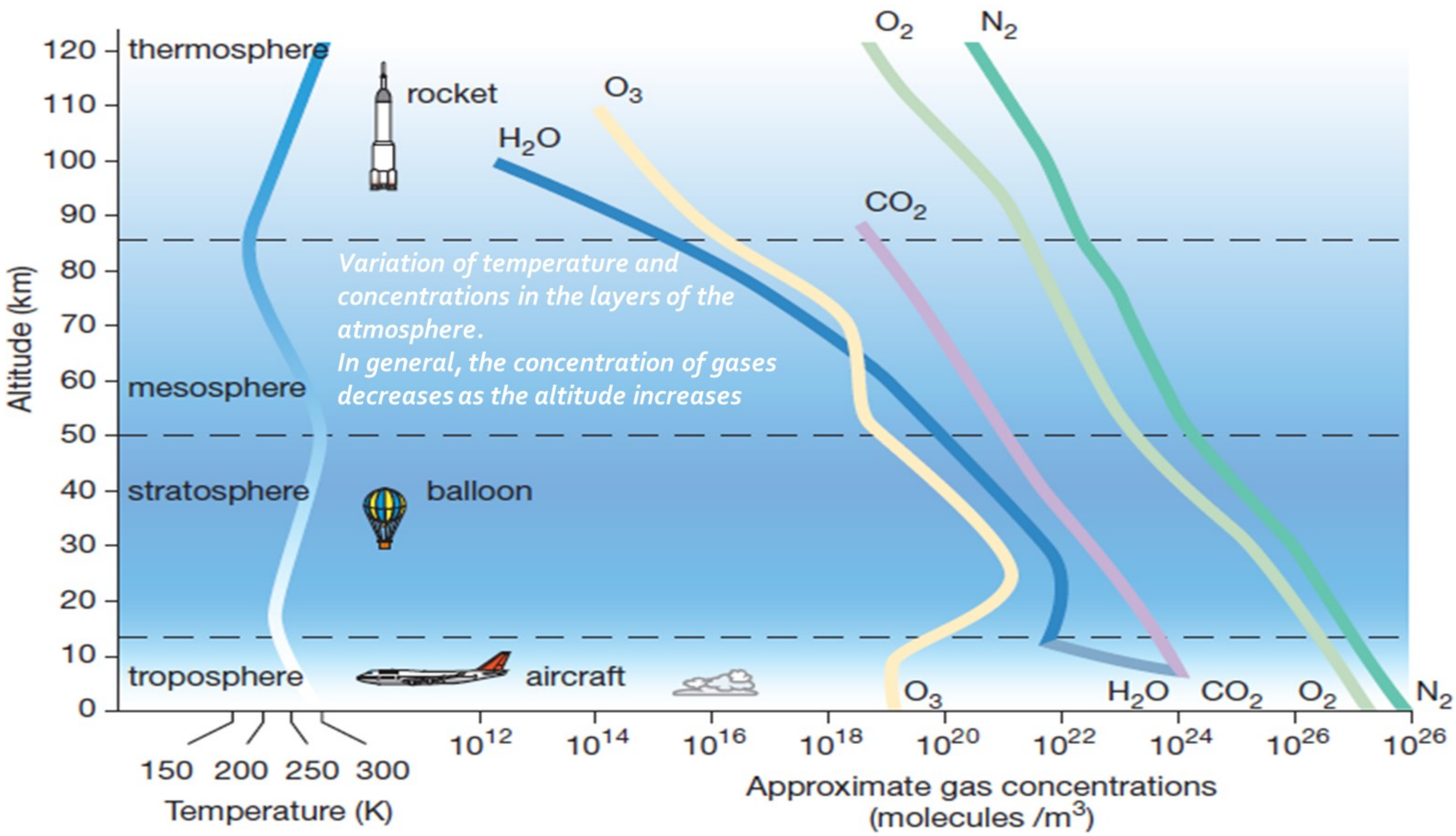

Figure 1 Layers of the Atmosphere (Lukins et al 2016[5])

Between each of these four layers thermal boundaries exist, where the temperature gradient changes direction - these are defined as **pauses**[6].

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[4] The exosphere is now considered by some atmospheric scientists (e.g. University Corporation for Atmospheric Research UCAR) to be part of the Earth's atmosphere; however the standard four (4) layers are included in this discussion.

[5] Lukins N., Elvins C., Lohmeyer P., Ross B., Sanders R. & Wilson G. (2016) *Heinemann – Chemistry 1 Enhanced* 4th Edition, Pearson Australia, Melbourne, Victoria Australia 8012 [Figure 18.2, p.314].

Based on the temperature profile, the Earth's atmosphere is categorized into **four main layers: (1) the troposphere, (2) the mesosphere, (3) the stratosphere and (4) the thermosphere.**

These layers are separated from each other by **pauses** – where the temperature profile reverses direction.

THE TROPOSPHERE

From a human perspective, it is the troposphere that has the most day-to-day influence on our lives as it is the closest to the Earth's surface and impacts on us through the weather and associated phenomenon. The troposphere has following key attributes:

- It extends an average of 11 km from the surface of the Earth, however its height varies with latitude from ~18 km[1] at the equator to ~8 km at the poles.
- Temperature declines with height in the troposphere - from the Earth's surface (~15°C), to the upper limit (~-55°C)[7]. This is an average rate of decline of ~6.5°/km. [2]
- Air is continually circulating within the troposphere due to convection currents[8]. Convection currents are one of the key drivers for the weather phenomena experienced on Earth. Figure 2 depicts the accumulation of cloud formations which are a feature of the troposphere.

Figure 2 Photograph of cloud formations within the troposphere[9]

- The upper limit of the troposphere is known as the '**tropopause**'[2] and is delineated by a marked temperature inversion[10].
- Air pressure and density also decrease with height.

[6] Imlay-Gillespie I. and Huxley C. (2002) *Earth and Environmental Science – The Preliminary Course*, Cambridge University Press, Melbourne VIC 3207, Australia.

[7] Marshak S. (2001) *Earth: Portrait of a Planet*, W.W. Norton & Company Inc., New York, USA.

[8] Source: https://scied.ucar.edu/shortcontent/troposphere-overview [Accessed: 3 October 2018] Credit Randy Russell UCAR.

[9] Source: https://courses.lumenlearning.com/earthscience/chapter/weather-processes-and-systems/ [Accessed: 3 October 2018]

[10] A 'temperature inversion' refers to the occurrence of a typically warmer layer of air overlying a cooler body of air.

- The troposphere accounts for 75-80% of the total gases of the Earth's atmosphere, including most of the water vapour and aerosols.[2]

The **troposphere** is the lowest level in the atmosphere and extends from the Earth's surface to ~11km, at is upper limit, which is known as the **tropopause**. Overall air temperature decreases with height.

The troposphere is the layer within which global weather patterns occur.

THE STRATOSPHERE

The stratosphere is the second layer of the atmosphere and has the following key attributes:

- It extends from 11km to 50km and may be separated into two key zones, based on the temperature profile:
    (1) Lower stratosphere – characterized by a relatively constant temperature profile, from 11km to 25km.
    (2) Upper stratosphere – characterized by a steady increase in temperature, from 25km to 47-50km.
- Overall the air temperature profile increases with altitude, from ~-55°C at its base (the tropopause), to 0-5°C at its upper limit (the **stratopause)**[7]. This is the opposite temperature effect to what occurs in the underlying troposphere.
- A consequence of this thermal stratification is that the stratosphere is a relatively stable layer[11]. This is because it does not have the large scale convection currents driving the air turbulence present in the troposphere. And it is due to this stability, and the low density, that commercial jets often attain their final cruising altitude in this layer – refer to Figure 3.

Figure 3 Photograph of a commercial jet flying in the lower stratosphere[12].

- Another consequence of this thermal stratification and stability is that gases (e.g. F-gases) and particulate matter (e.g. volcanic ash) can accumulate and take a significant amount of time to disperse. This accumulation can have unintended consequences, particularly if derived from man-made sources.
- The structure of the stratosphere can be substantially impacted by seasonal changes, dependent on latitude[2].

[11] Source: https://scied.ucar.edu/shortcontent/stratosphere-overview [Accessed: 3 October 2018] Credit Randy Russell UCAR

[12] Source: https://www.standard.co.uk/lifestyle/travel/direct-flights-from-london-to-australia-will-go-on-sale-next-month-a3488376.html [Accessed: 2 October 2018]

- In terms of gas composition, a key characteristic of the stratosphere is the presence of 90%[13] of the ozone present in the Earth's atmosphere.
    - This accumulation of ozone is known as the **'ozone layer'**. Ozone is a molecule containing three oxygen atoms (O_3) which, when present in sufficient quantities, protects the Earth's surface from dangerous UV radiation from the Sun. It does this by absorbing the UV radiation and converting this into thermal energy, hence the increase in temperature gradient with height.
    - Ozone and it action in the atmosphere will be discussed in more detail in Section 4.3.
- A second key characteristic of the gas composition of the stratosphere is that it is largely devoid of water vapour – a key contrast with the underlying troposphere.

The stratosphere is bound by the tropopause at its lower limit and the stratopause at its upper limit. And overall temperature increases in the stratosphere which results in a relatively stable layer with little mixing.'

A key feature of the stratosphere is the presence of the ozone layer.

SCIENCE AS HUMAN ENDEAVOUR – DISCOVERY OF THE TROPOPAUSE AND THE STRATOSPHERE

EXCERPT from Barry and Chorley (2010)[14]:

"Early scientific exploration of the upper atmosphere began with manned balloon flights in the mid-nineteenth century. Notable among these was the ascent of Glaisher and Cox in 1862. Glaisher lost consciousness due to lack of oxygen at about 8800m altitude and they barely survived the hypoxia. In 1902 Teisserenc de Bort in France reported a totally unexpected finding; that temperatures ceased decreasing at altitudes around 12km. Indeed, at higher elevations temperatures were commonly observed to begin increasing with altitude.

Figure 4 Photograph of Glaisher and Cox 1862.[15]

[13] Source: https://scied.ucar.edu/ozone-layer [Accessed: 4 October 2018]

[14] Barry R.G. and Chorley R.J. (2010) *Atmosphere, Weather and Climate*, page 35, Ninth Edition, Routledge, OXON OX14 4RN, England.

[15] Source: http://historythings.com/crazy-science-5-bizarre-things-victorians-research/. Accessed: 29 September 2018

The terms troposphere (turbulent sphere) and stratosphere (stratified sphere) were proposed by Teisserenc de Bort in 1908; the use of 'tropopause' to denote the inversion or isothermal layer separating them was introduced in Great Britain during World War 1."

THE MESOSPHERE

The mesosphere is the third layer of the atmosphere and has the following key attributes:

- It extends from 50 to 85km.
- It does not absorb energy from the Sun due to an absence of greenhouse gases within this layer. Consequently, the mesosphere is the coldest layer in the atmosphere with the air temperature profile decreasing with altitude, from 0-5°C at its base (the stratopause), to -90°C[16] at its upper limit (the **mesopause)**
- Primary gases present are O_2, N_2 and CO_2, similar to the troposphere; however the density of gas particles is significantly lower[17].
- Meteors disintegrate within this layer; as a result, the remnant particles results in higher concentrations of iron (Fe) and other metals in this layer[16] – refer to Figure 5.

Figure 5 Artist impression of meteorites entering the mesosphere[18]

- Depending on conditions, 'noctilucent' clouds can form at the poles – refer to Figure 6.
- Movement of particles in the mesosphere can be impacted by underlying changes in the stratosphere and troposphere.

Compared to the underlying layers (troposphere and stratosphere), scientific understanding of the mesosphere is relatively less well developed.

The mesosphere is bound by the stratopause at its lower limit and the mesopause at its upper limit. Temperature decreases with height.

Meteors burn up and are destroyed within this layer.

[16] Source: https://scied.ucar.edu/shortcontent/mesosphere-overview [Accessed: 9 October 2018]

[17] Source: https://www.britannica.com/science/mesosphere [Accessed: 10 October 2018]

[18] Source: https://i.pinimg.com/736x/12/c0/70/12c070b2cee997ef8fead9239316e513.jpg [Accessed: 2 October 2018]

Figure 6 Noctilucent clouds are a relatively rare phenomena occurring in the mesosphere at the poles[19].

THE THERMOSPHERE

The thermosphere (also known as the ionosphere) is the fourth and final layer of the atmosphere, and has the following key attributes:

- It extends from 85 to >500 km[20].
- Overall, the temperature profile increases in the thermosphere due to the absorption of radiation from the Sun, and can reach nominal temperatures in excess of 1000°C.
    - This is the first layer of the atmosphere to be impacted by radiation from the Sun. Consequently the gas particles present in this layer can be heated to extreme temperatures.
    - However, due to the very low density of particles in this layer, the impact of these temperatures is less consequential i.e. there are very few particles to transfer heat energy.
- The molecular chemistry changes in the thermosphere, whereby *"the gases become somewhat separated based on the types of chemical elements they contain. Energetic ultraviolet and X-ray photons from the Sun also break apart molecules in the thermosphere. In the upper thermosphere, atomic oxygen (O), atomic nitrogen (N), and helium (He) are the main components of air"*[20].
- The Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights) occur within the thermosphere.

Above the thermosphere, at heights greater than 500km[2] from Earth (dependent on solar activity), the atmosphere transitions into the exosphere – this boundary is known as thermopause.

The transition region between the Earth's atmosphere and space is an active area of scientific research, as demonstrated by the recent deployment by NASA of the GOLD (Global-scale Observations of the Limb and Disk) satellite on January 25 2018. The aim of the GOLD program is to investigate and collect data on the interface between the atmosphere and space – refer to Figure 7.

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[19] Source: https://www.mnn.com/earth-matters/climate-weather/blogs/electric-blue-night-clouds-expanding-around-globe-says-nasa [Accessed: 9 October 2018]

[20] Source: https://scied.ucar.edu/shortcontent/thermosphere-overview [Accessed: 10 October 2018]

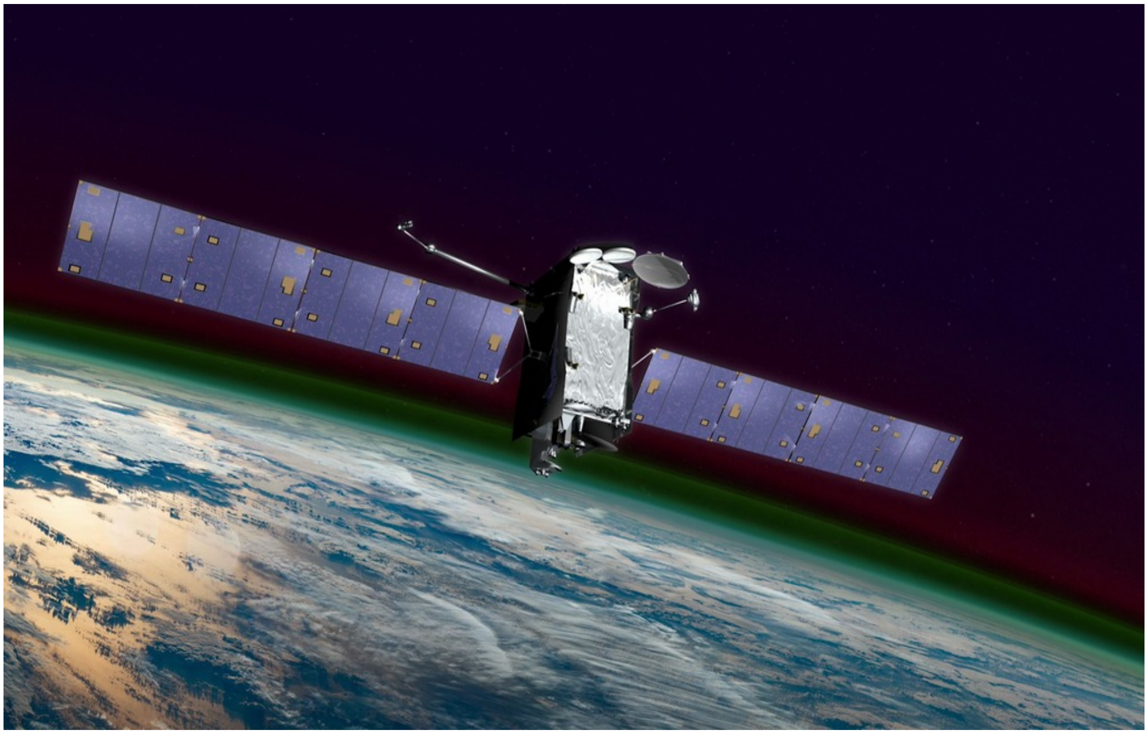

Figure 7 Photograph of GOLD (Global-scale Observations of the Limb and Disk) satellite – a NASA mission launched on January 25 2018 to investigate the boundary between the Earth's atmosphere and space. [21]

4.2.3 VARIATION IN TEMPERATURE WITHIN THE ATMOSPHERE

The air temperature varies within and between each layer of the atmosphere and may be summarized as follows – refer to Table 2.

Table 2: Variation in temperature within the Earth's atmosphere

Layer/Boundary	Distance from Earth Surface (km)[22]	Temperature (°C)	
		Trend with Altitude	Range
Troposphere	0 - 11	Decreasing	15 to -55[8]
Tropopause			
Stratosphere	11 - 50	Increasing	-55 to 0-5[2]
Stratopause			
Mesosphere	50 - 85	Decreasing	0 to -90[2]
Mesopause			
Thermosphere	85 - >500	Increasing	-90 to >500

An overall summary of the key components of the atmosphere is outlined in Figure 8:

[21] Source: https://svs.gsfc.nasa.gov/vis/a010000/a012800/a012823/12827_GOLD_SES14satellite.00300_print_print.jpg [Accessed: 2 October 2018]

[22] Note – the heights detailed for each boundary between the layers varies slightly according to different authors. Hence these are a broad guide.

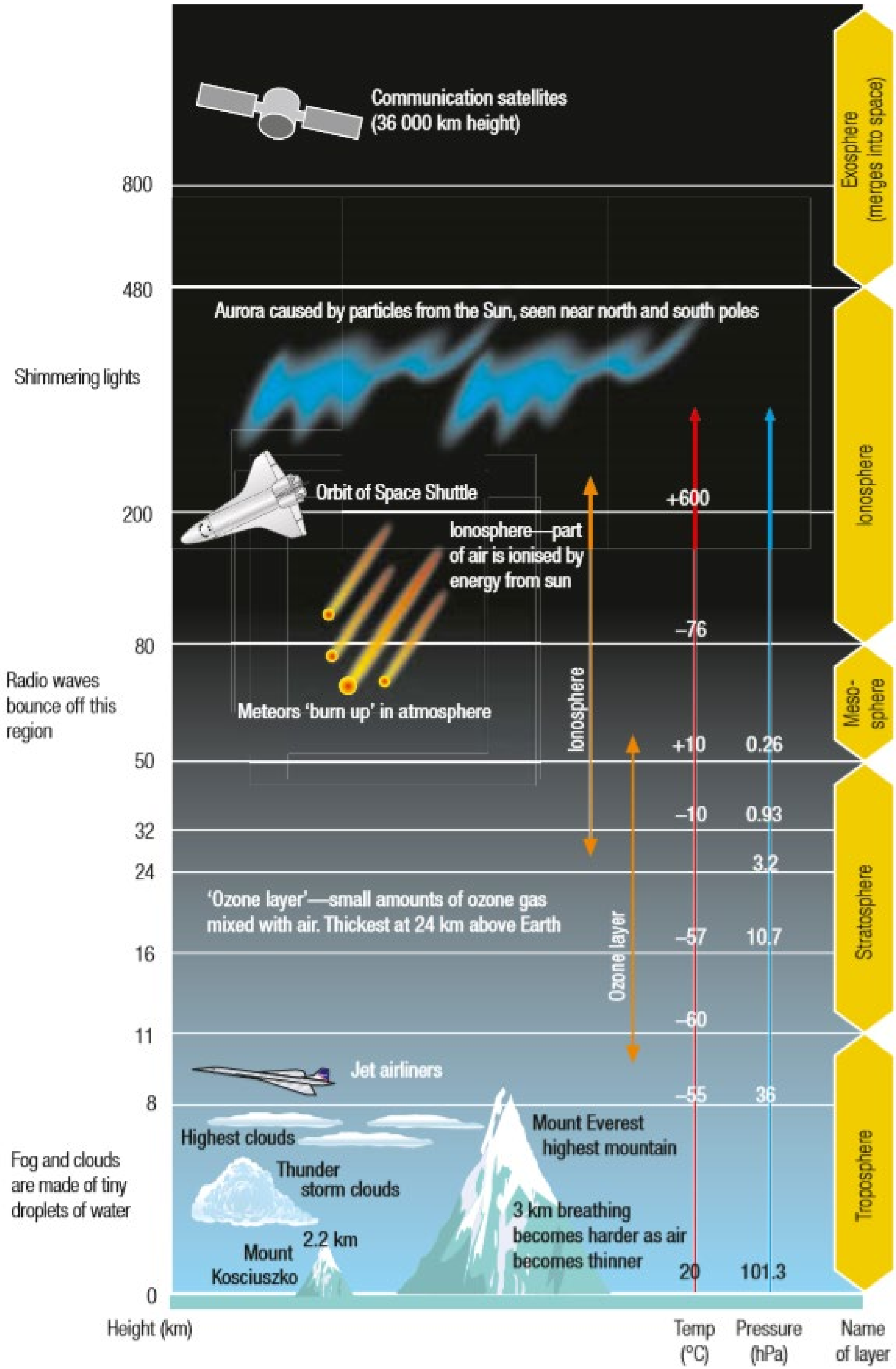

Figure 8 Summary diagram detailing the atmosphere and its four main layers. Note – the ionosphere is often used inter-changeably with the thermosphere (Source: Quinton et al., 2012)[23].

KEY LEARNING OUTCOMES (SACE 2018)

[23] Quinton G., Cash S., Tilley C., Craven E., Laidler G. and Kennedy E. (2012) Oxford Big Ideas Australian Curriculum Science 10' p.93, Oxford University Press VIC 3205 Australia

From the 'Subject Outline' developed by SACE (2018)[24], the following are the key learning outcomes:

4.2		**Derivation of the Earth's Atmosphere**	**Check**
	4.2.1	The modern atmosphere has a layered structure: the troposphere, mesosphere, stratosphere, and thermosphere.	☐
		Discuss the key features that characterize the four main layers of the atmosphere	
	4.2.2	Describe the variation of temperature with altitude in the layers of the atmosphere.	☐

QUESTIONS

Question 1 (2 marks)

Describe the composition of the Earth's current atmosphere

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Question 2 (8 marks)

Outline the structure of the Earth's atmosphere, including how the boundaries between each layer, are defined.

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[24] Source: https://www.sace.sa.edu.au/web/earth-and-environmental-science/stage-1/planning-to-teach/subject-outline [Accessed: 23 August 2018]

Question 3 (4 marks)

Identify within which atmospheric layer the 'ozone layer' is present? And describe why ozone is important for sustainability of the Earth's climate?

Question 4 (2 marks)

Summarize how the temperature changes with altitude

Question 5 (2 marks)

Identify which layer has the highest proportion of water vapour present? And how does this impact conditions within this layer?

Question 6 - Extension (4 marks)

The following is a picture of the Aurora Australis published in the Mercury newspaper, Tasmania[25].

The spectacular aurora australis captured from Casey Station in the Antarctic. Picture: © Gordon Tait/Australian Antarctic Division

Research and explain how the Aurora Australis, and its northern cousin, the Aurora Borealis, occur, including which layer(s) of the atmosphere these effects impact.

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Question 7 – Extension (5 marks)

[25] Source: https://www.themercury.com.au/lifestyle/keep-your-eyes-peeled-tassie-the-aurora-australis-is-now-on-show/news-story/b3b2112a2b79a81fdb90347ba9d3eb36 [Accessed: 9 October 2018]

Read the following article -

ABC NEWS

Satellite built by University of Adelaide launched into space by NASA

Updated Wed 19 Apr 2017, 9:21am

The first Australian-built satellites in 15 years have been launched into space by NASA after being developed by Australian universities.

One of the miniaturised satellites called the CubeSat was built over four years by about 50 University of Adelaide (UOA) staff and students.

It is one of three "nanosatellites" developed in Australia as part of a research project involving Australian universities under the European-funded project, QB50 — an international network of 50 CubeSats.

They will play a key role in investigating the thermosphere — a layer of atmosphere from about 95 kilometres to 500 kilometres from the Earth's surface — with the aim of increasing understanding of climate and weather modelling.

The satellite will be deployed from the International Space Station into the thermosphere in about one month to take measurements.

RELATED STORY: Satellite launch to mark Australia's return to space

Fast facts:

- A cargo space craft launched from Cape Canaveral Air Force Station
- The satellite, built by the University of Adelaide, is about the size of a loaf of bread
- The mini satellite will be deployed from the International Space Station in about a month
- About 50 students and a dozen staff have worked on the project

Research fellow at UOA's School of Mechanical Engineering Mathew Tetlow said it had been a huge learning experience.

"It's a great feeling," Dr Tetlow said.

> "I mean we went into it with the objective of developing skills and developing capability and knowledge and it's been a very rocky road.

"They changed launches on us. They threw in a whole lot of requirements late in the piece, so it's been a real rollercoaster ride but it's been an absolutely fantastic experience and a great experience for the state."

Hopes that Australia will return to space industry

The South Australian State Government granted $300,000 towards the development of the University of Adelaide satellite.

Dr Tetlow said it was just the beginning of Australia's involvement in the billion-dollar space industry.

"I think it's really important that we have a bit of momentum now," he said.

"There's a lot of discussion both at the federal and state level about the growing space industry and I think it's really important that we leverage that and build this into something that's meaningful and sustainable."

'Really big firsts for Australia'

Australian Centre for Space Engineering Research (ACSER) director at the University of NSW Andrew Dempster, who is also a member of the advisory council of the Space Industry Association of Australia, said there had only been two previous Australian satellites launched in 1967 and 2002.

> "So we've got more hardware in space today than Australia's had in its history," Mr Dempster said.

Iver Cairns, from the University of Sydney, was at the launch and he said it was a big day for Australian space research.

"These will be the fourth, fifth and sixth satellites ever built in Australia that are launched into space, first ones going to the international space station," Professor Cairns said.

> "The first CubeSats that are Australian going into space, so there are some really big firsts qualitatively for Australia.

"It's a very exciting thing to do, it's something that we in Australia ought to be doing more regularly, and we hope this is the start of a real Australian space effort."

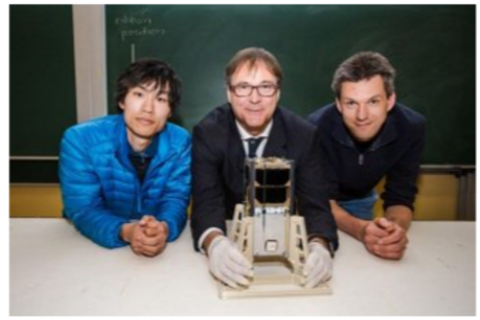

PHOTO: PhD student Jiro Funamoto, Professor Iver Cairns and electronics engineer Wayne Peacock with INSPIRE-2. (Supplied: University of Sydney)

The launch was aired live on NASA TV just after midnight.

Based on the article *'Satellite built by University of Adelaide launched into space by NASA'* [26], complete the following questions:

(i) What is the Qb-50 project? (1)

____

____

(ii) Which layer in the atmosphere was the focus for the satellite deployment and data acquisition in this project? And why? (2)

____

____

____

____

(iii) Why is it important for these types of projects to proceed? i.e. why is this science important to our society. (2)

____

____

____

____

Question 8 - Extension[27] (3 marks)

[26] Source: http://www.abc.net.au/news/2017-04-19/adelaide-built-satellite-launched-into-space-by-nasa/8451834 [Accessed: 4 October 2018]

Australian space startup Fleet Space Technologies has an awesome new mission control centre

PETER FARQUHAR
JUL 27, 2018, 3:30 PM

Australian space startup Fleet Space Technologies has a new mission control centre and it looks exactly how an Australian space mission control centre should look:

Picture: Fleet Space Technologies

The ground station at Red Banks Reservoir, Pinkerton Plains in South Australia will operate for 24 hours a day and allow Fleet to track and receive data from nanosatellites, including its own which are set to launch this year.

It is adorable.
It's also just about the best visual example we've seen of just how accessible the space industry is becoming if you've got the kind of tenacity and drive Fleet CEO Flavia Tata Nardini brings to a startup.

Nardini founded Fleet in Adelaide in 2015 with fellow engineer Dr Matthew Tetlow, entrepreneur Matt Pearson, and about $5 million from a couple of VCs.

(i) Who is Flavia Tata Nandini (research required)? (1)

[27] Source: https://www.businessinsider.com.au/australian-space-startup-fleet-space-technologies-has-an-awesome-new-mission-control-centre-2018-7 [Accessed: 4 October 2018]

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___

(ii) Why is it important to South Australia, and Australia, for start-ups such as Fleet Space Technologies, to be involved in the future of space exploration? (2)

___

___

___

___

ACTIVITIES

- Investigate the structure of the Earth's atmosphere[24], e.g. at: http://glencoe.mheducation.com/sites/0078778026/student_view0/unit5/chapter15/virtual_lab.html
- Construct a scaled drawing (on a very large piece of paper) of a part of the Earth's cross-section, including the layers of the atmosphere. Include, for example, the highest mountain, the deepest ocean trench, and the altitudes of the highest-flying aircraft and Earth-orbiting satellites[24].
- Construct a scaled drawing of the layers of the atmosphere that includes a plot of temperature vs height[24].

KEY TERMS

Air, greenhouse gases, troposphere, stratosphere, mesosphere, thermosphere, ionosphere, exosphere, pauses, tropopause, stratopause, mesopause, temperature, altitude, air pressure, air density, convection currents, thermal stratification, ozone, ozone layer, Aurora Borealis, Aurora Australis

4.4 Earth’s energy balance

The earth’s source of energy is mainly from the sun. There is heat remaining from when the earth was formed and the decay of radioactive materials. The circulation of this heat drives plate tectonics. The earth energy balance in the atmosphere occurs as incoming energy is used and returned to space. The earth’s temperature remains constant if these are balanced. Refer figure 6.

- 100% of the energy entering earth’s atmosphere comes from the sun.
- ~50% of the incoming energy is absorbed by the earth’s surface i.e. the land and oceans.
- ~30% is directly reflected back to space by clouds, the earth’s surface and different gases and particles in the atmosphere (the earth's albedo is 0.3 on average).
- ~20% is absorbed by the atmosphere and clouds. (https://climate.ncsu.edu/edu/EnergyBalance)

Globally there is an imbalance in solar energy received and the earth attempts to balance this out by atmospheric circulation and weather patterns. Currents in the wind and ocean water carry this energy from the tropic to the poles.

Albedo is an expression of the ability of surfaces to reflect sunlight (heat from the sun). Light-coloured surfaces return a large part of the sunrays back to the atmosphere (high albedo). Dark surfaces absorb the rays from the sun (low albedo). Albedo peaks twice during the year. The first peak occurs when the Antarctic sea-ice is at its winter maximum. The second larger peak occurs when there is snow cover over much of the Northern Hemisphere

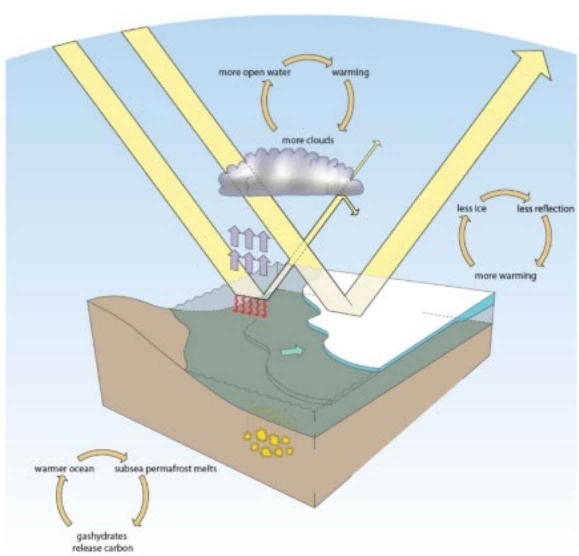


Figure 5 [*http://www.npolar.no/npcms/export/sites/np/images/portal-pages/2013/albedo-sea.jpg_680232009.jpg*](http://www.npolar.no/npcms/export/sites/np/images/portal-pages/2013/albedo-sea.jpg_680232009.jpg)

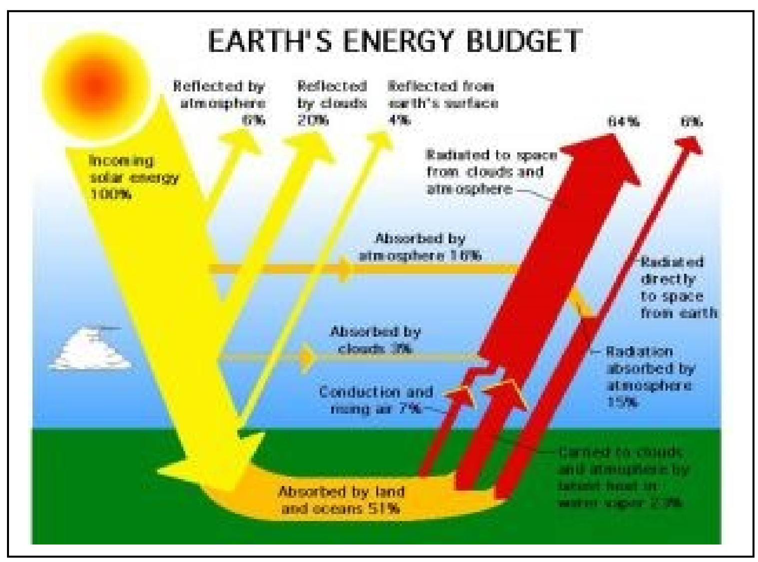


Figure 6 Earth's energy budget 1

Albedo is an important part of climate change. Ice has high albedo and reflects most solar radiation back into the atmosphere. As sea surface temperatures increase in the Artic then sea ice melts. The removal of sea ice leads to further sea warming as sea has a lower albedo and will absorb more radiation from the sun.

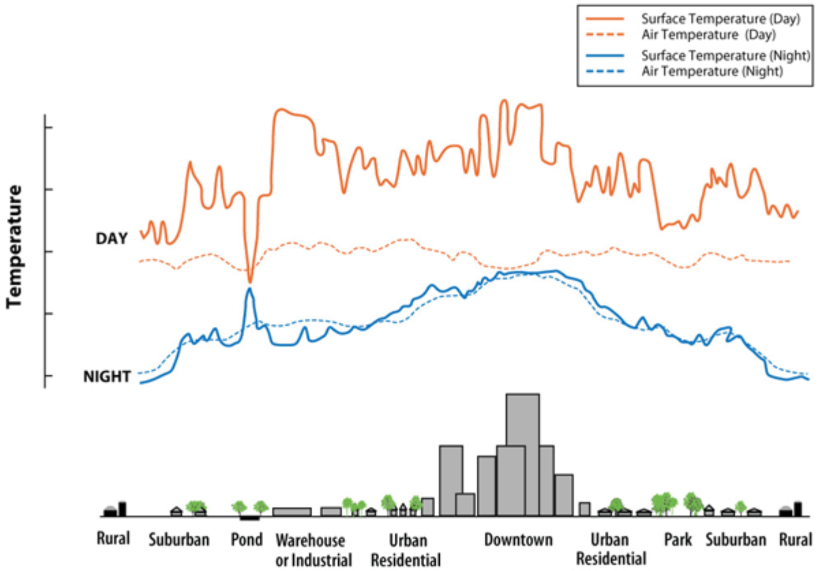


Figure 7 https://climate.ncsu.edu/images 1

<u>Figure 7. Focus questions</u>

1. Do all surfaces receive the same amount of energy from the sun near the same location?

2. Name surfaces that are best at reflection of sunlight and so have high albedo rating?

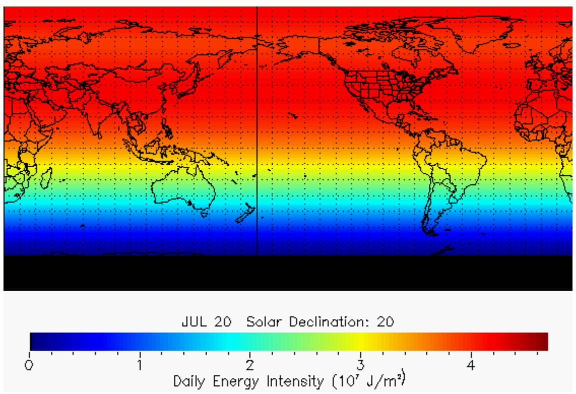
3. Name surfaces that are low at reflection of sunlight and so have low albedo rating?

4. Describe the pattern seen in the day surface and air temperatures.
Do they follow a similar pattern? Why of why not?

5. Describe the pattern seen in the night surface and air temperatures.
Do they follow a similar pattern? Why of why not?

If ice sheets are added to continents this raises the albedo or reflectivity of the surface. This means less sunlight is absorbed by the ground and so less energy such as infrared are reradiated into the atmosphere. The contribution to the annual mean temperature and the atmospheric heat budget is less and this encourages more ice to form. This acts as a positive feedback which amplifies this small change in the system. This is an example of how the effects of albedo can affect the climate.

Figure 2 above demonstrates the effect of albedo due to different



http://oceanmotion.org/html/resources/solar.htm

Solar Energy animation. Allows user to observe the solar energy intensity on the earth's surface at different times during the year.

figure 8 ***Activity:***

Practical activity: Reflection of Light from Dark and Light surfaces

Aim: To understand the process of light reflecting from surfaces. To design a method to carry out the practical, listing the variables and organizing a results table.

Materials:

- Ice cubes made of water and some containing carbon (use activated carbon capsule) or sprinkle the carbon onto the surface of the ice cube.
- Light source e.g. Lamp
- Stop watch
- Thermometer , heat sensor

Fill in table

Experimental variables or factors	
Independent variable	
Dependent	
Controlled factors	
Uncontrolled factors	

Design a method to carry out this activity. You need to consider whether you can collect quantitative or qualitative data.

Prepare a results table.

Results:

Discussion questions.

1. Why might it be important the ice cubes are identical?
2. What were the limitations in performing the practical and how might they be minimized.
3. How might the information from this practical be applied to our understanding of ice sheets in the Artic or Antarctica?

Worksheet Questions

1. Explain what is meant by the earth's energy budget.
2. What does it mean if a surface has a low albedo reading?
3. What factors locally and globally will affect climate?
4. In the Arctic region the amount of sea ice is decreasing. Is this a natural cycle? Why are Polar bears under threat and found in closer proximity to humans?
5. Explain what is meant by a positive feedback in the environment.
6. Consider the graph of Albedo against height of vegetation

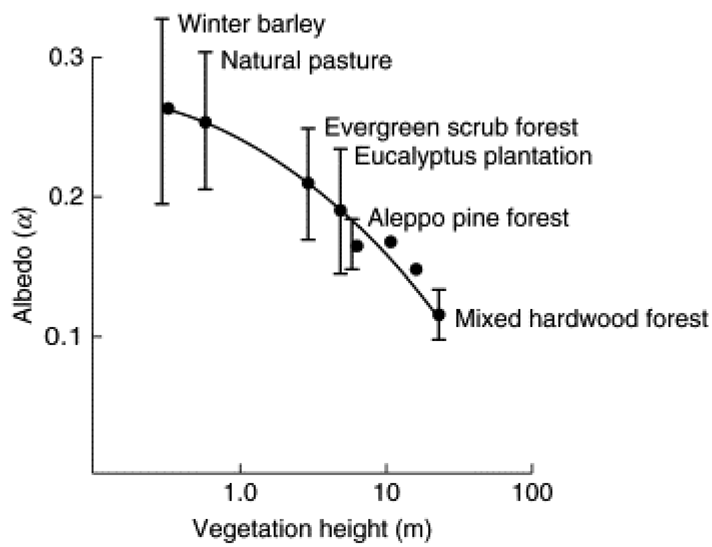


Figure 9 https://www.sciencedirect.com/topics/earth-and-planetary-sciences/albedo

(i) Name a vegetation type that has a high albedo and what does this mean?

(ii) What would be the advantages of a mixed hardwood forest with a low albedo?

(iii) What conclusion can you draw from the graph below? Could this information have any application?

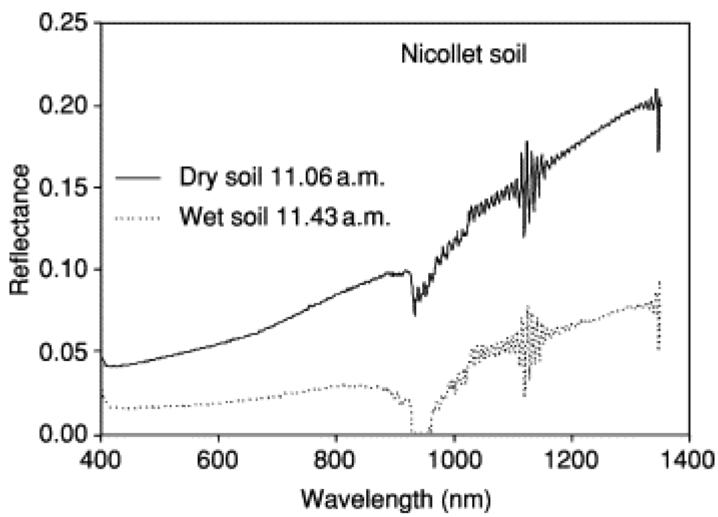


Figure 10 https://www.sciencedirect.com/topics/earth-and-planetary-sciences/albedo

4. THE ATMOSPHERE

4.5 GREENHOUSE GASES & THE ATMOSPHERE

'Greenhouse gases' (GHG) are gases which trap re-radiated solar heat within the atmosphere[1] and act to maintain the Earth's atmosphere at habitable temperatures – this process is known as the natural 'greenhouse' effect (GHE). Without the presence of GHGs the Earth's temperature would be substantially lower.

Whilst the 'natural' GHE, rather the enhanced' GHE which is primarily been driven by man-made (anthropogenic) sources with potentially unprecedented climate outcomes in this century.

4.5.1 GREENHOUSE GASES (GHG) IN THE ATMOSPHERE – PRESENCE AND ACTION

PRESENCE OF GREENHOUSE GASES (GHG) IN THE ATMOSPHERE

The primary greenhouse gases (GHG) gases present in the Earth's atmosphere include:

- carbon dioxide (CO_2),
- methane (CH_4),
- nitrous oxide (N_2O) and,
- fluorinated gases (F-gases)

Figure 1 presents the overall contribution from each of the four main GHGs together with diagrams of each of the molecules.

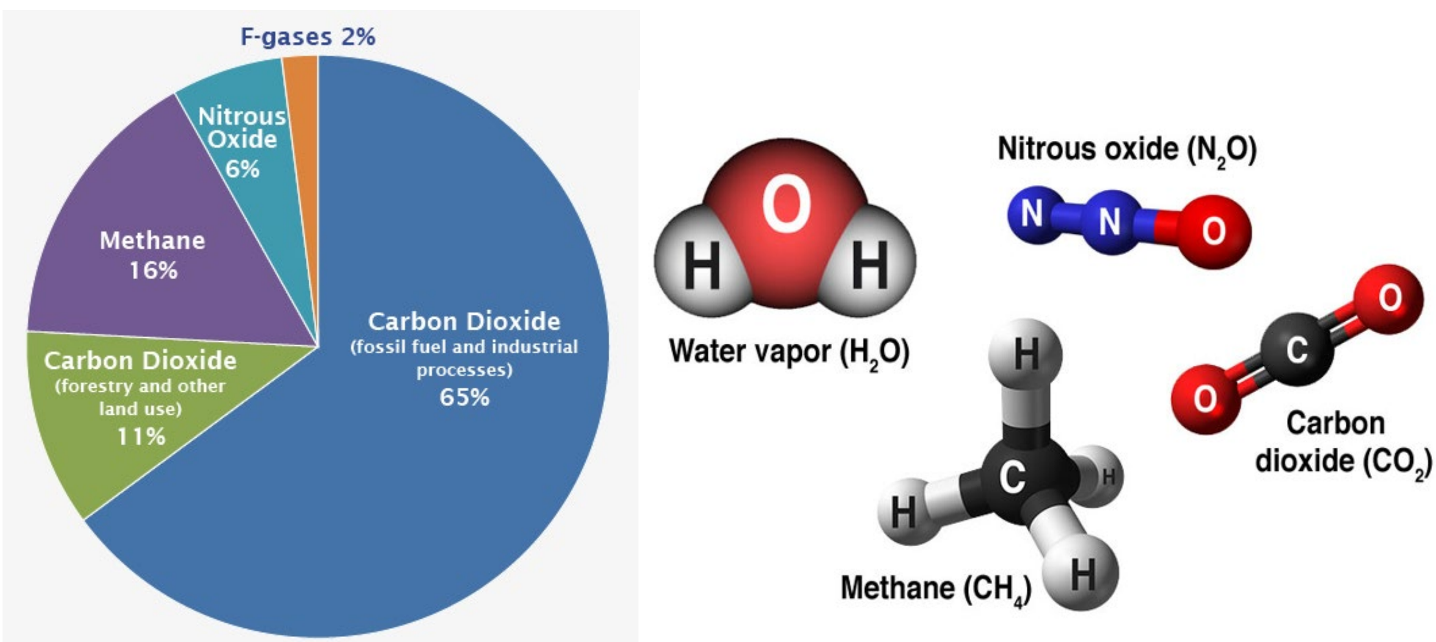


Figure 1 Global greenhouse emissions by gas (based on 2010 data[1]) and their molecular structure[2]

Water is also a GHG, however it is not typically included in discussions on GHG, because it acts as a 'feedback'[2] mechanism for the Earth's climate i.e. whilst water content in the atmosphere increases with temperature, at the same

[1] EPA (2018) Overview of Greenhouse Gases, Environmental Protection Agency, U.S.A. Last updated on April 11, 2018 https://www.epa.gov/ghgemissions/overview-greenhouse-gases. [Accessed: 11 September 2018

[2] Source: https://climate.nasa.gov/causes/ [Accessed: 7 November 2018]

time there is an increase in cloud cover and precipitation which returns water back to earth and oceans as part of the global water cycle.

The concentration of GHG has increased from human activity as a result of the expanding global population and industrialization. A summary of the key GHGs and their main sources are outlined in Table 1 - further details on each of these key GHGs follows.

GHG	Main Source	Human Activity
Carbon dioxide (CO_2)	Combustion of fossil fuels (coal, petrol, oil and gas)	Transport, power production, industry, communications and land clearing (deforestation)
Methane (CH_4)	Anaerobic breakdown of plant materials	Energy production, increased emissions from livestock, landfill, biomass burning and waste treatment
Nitrous oxide (N_2O)	Reduction of nitrates by microbes	Use of nitrogenous fertilizers in agriculture, transportation and industry (nitric acid production); biomass burning
Fluorinated gases (F-Gases)	Refrigerants & aerosols propellants; solvents; packing materials	F-gases used in refrigerated air conditioning & aerosols

Table 1 Summary of the key greenhouse gases (GHGs) and their sources

There are four (4) main greenhouse gases (GHG) in the atmosphere: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and F-gases.

GHGs are derived from natural and man-made sources (exception F-gases which are synthetic).

CARBON DIOXIDE

Carbon dioxide (CO_2) is the principal GHG due to its volumetric impact. The primary man-made sources of CO_2 are related to the combustion of fossil fuels, with a far lower contribution by cement production – refer to Figure 2.

As is evident in Figure 2, prior to 1850 comparatively little CO_2 was derived from human activity. Since this period, with the advent of the industrial revolution (late 18th century) the concentration of CO_2 in the atmosphere has steadily increased. Then in the 1950's, a second trend emerged, related to the post-war period – this period is known the **'Great Acceleration'**. The Great Acceleration has resulted in a dramatic increase in global industrialisation and growth, resulting in a consequent increased in CO_2 emissions. And at present, the level of CO_2 is increasing by about 0.5%[3] per year globally; 4% of this increase is attributed to the U.S. alone[7].

About half of the CO_2 produced from human activity has accumulated in the atmosphere; the remainder has either dissolved in the oceans or has been used by plant life in photosynthesis via the Earth's natural carbon cycle.

To provide some perspective on the levels of CO_2 accumulating in the Earth's atmosphere, particularly since the 1950's, refer to Figure 3.

[3] Not validated

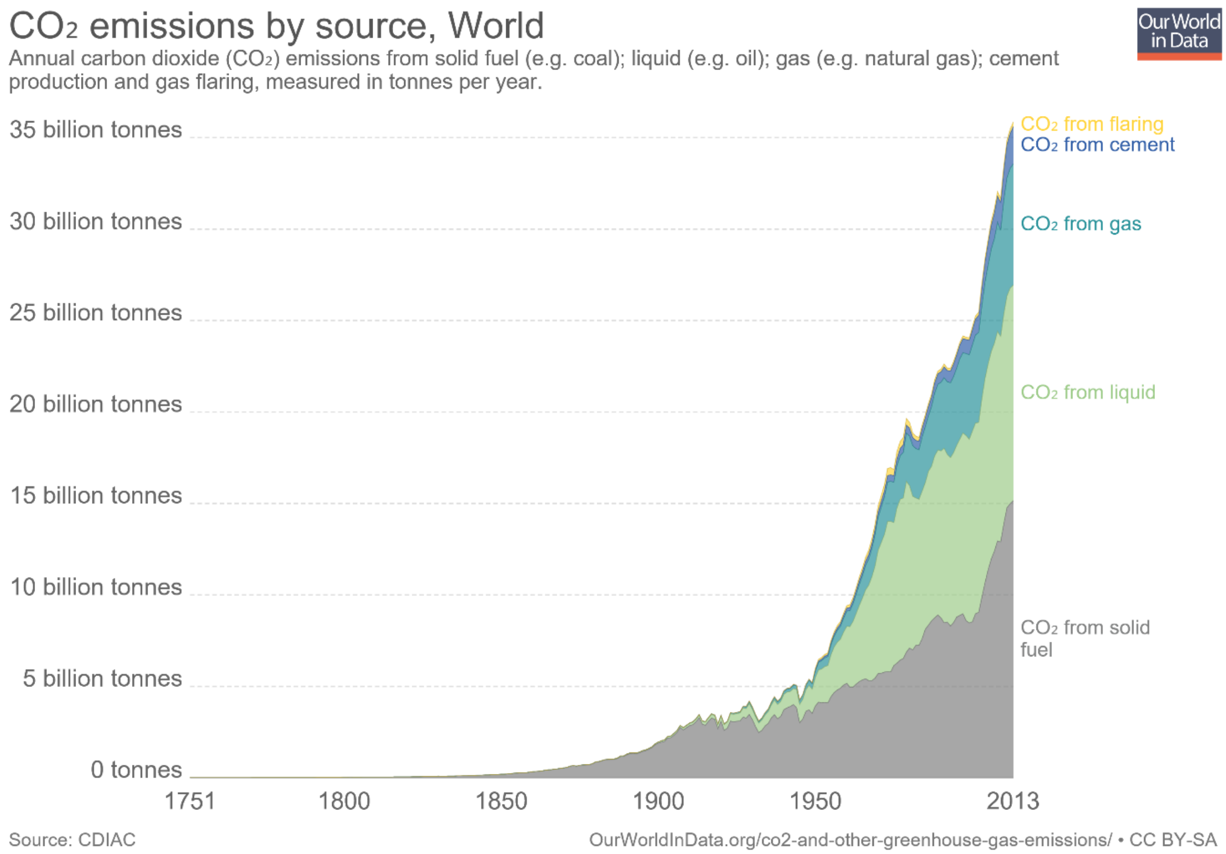


Figure 2 Carbon dioxide (CO_2) emissions by source[4]

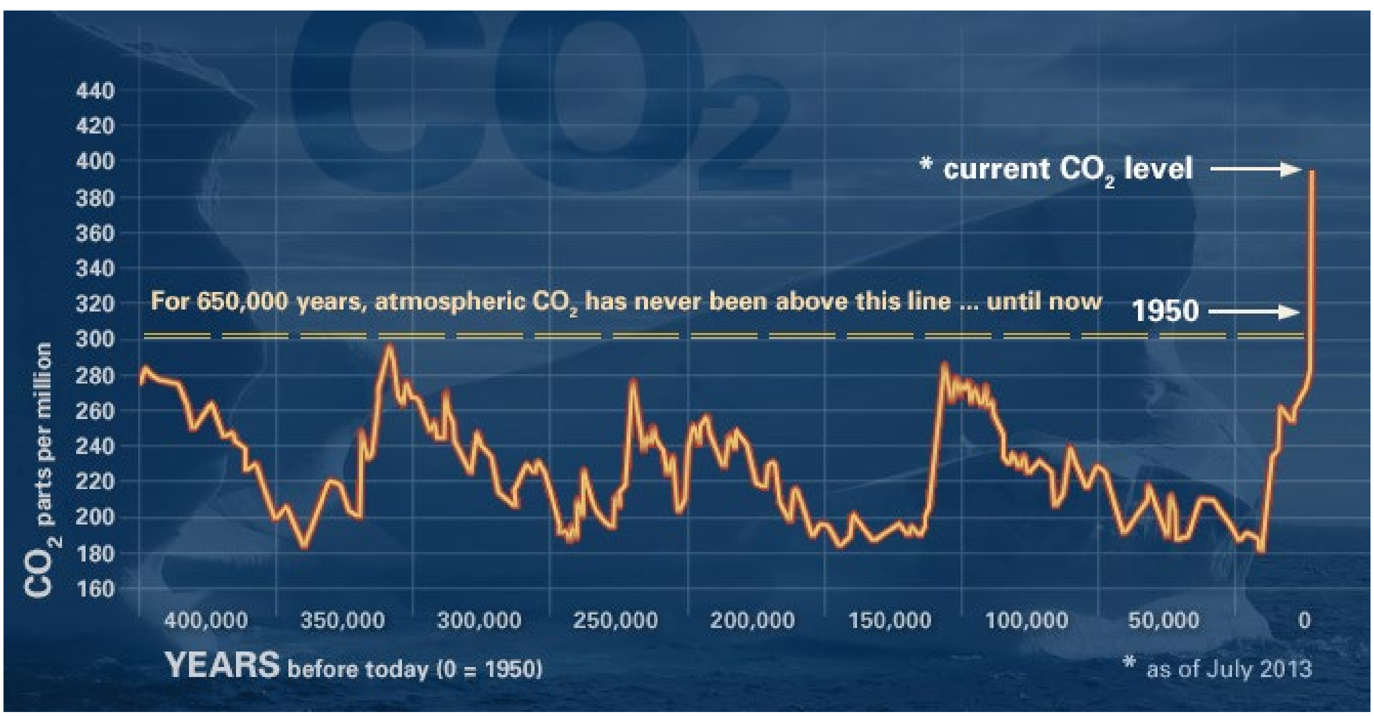


Figure 3 NASA Graphic depicting accumulation of atmosphere CO_2[5]

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[4] https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#the-long-run-history-cumulative-co2 [Accessed: 7 November 2018]

[5] Source: https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide/ [Accessed: 7 November 2018]

METHANE

Methane (CH_4) is the second most volumetrically significant GHG and, in comparison to CO_2, is more potent in terms of its heat absorption capacity (otherwise known as the 'global warming potential', GWP).

Methane is produced by bacterial action in the digestive tracts of ruminant animals (cattle and sheep). It also enters the atmosphere from rice paddies, termite mounds, natural gas fields, industrial activities, involving the burning of wood and fossil fuels, and garbage dumps, amongst other sources.

An overview of the methane emissions by sector is presented in Figure 4.

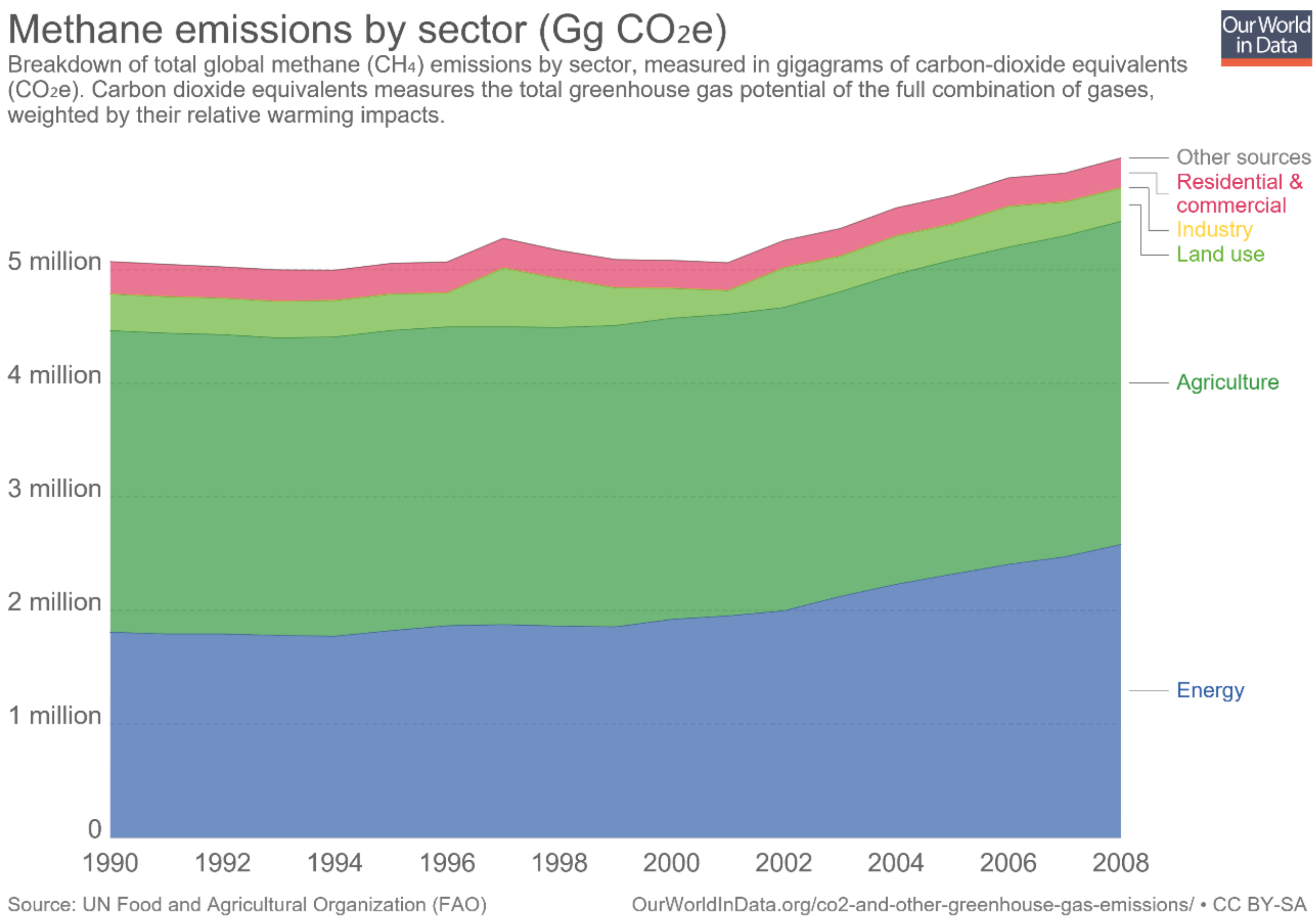

Figure 4 Methane (CH_4) emissions by sector[4]

NITROUS OXIDE

'Nitrous oxide emissions occur naturally through many sources associated with the nitrogen cycle… Natural emissions of N2O are mainly from bacteria breaking down nitrogen in soils and the oceans. Nitrous oxide is removed from the atmosphere when it is absorbed by certain types of bacteria or destroyed by ultraviolet radiation or chemical reactions.' (EPA 20186).

Whilst a large proportion of **nitrous oxide, N_2O**, occurs naturally within the atmosphere as part of the 'nitrogen' cycle, approx. 40% of N_2O is produced from human activity[6] and these emissions are increasing. Using the U.S emissions. as a reference point, the rate of increase of N_2O emissions is estimated to be ~4% p.a. as at 2016.

The human activities which are contributing to N_2O emissions include agriculture (use in soil management/fertilisers), transportation (by-product of fuel combustion) and industry.

An overview of N_2O emissions by sector is presented in Figure 5.

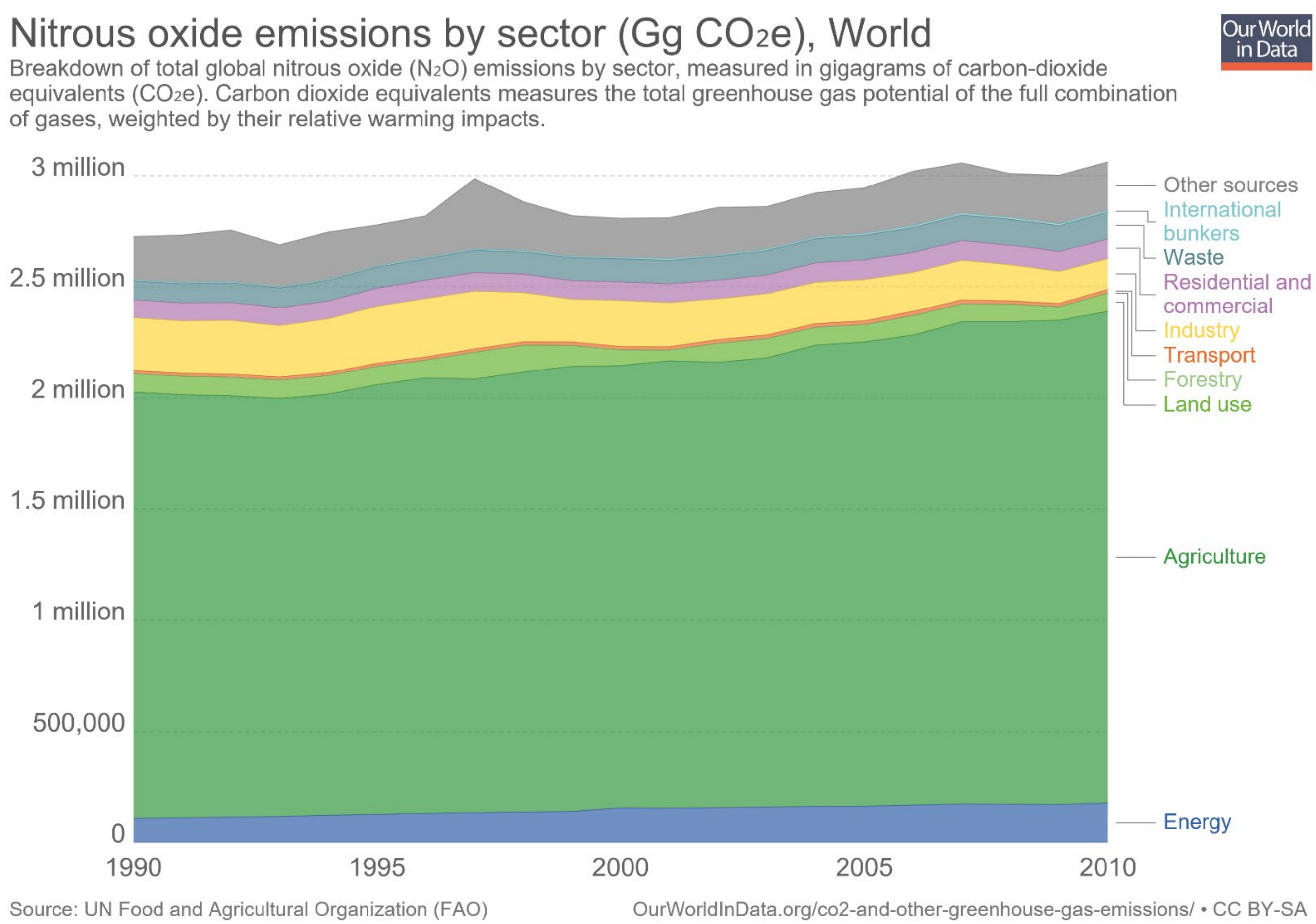

Figure 5 Nitrous oxide (N_2O) emissions by sector[4]

SYNTHETIC FLUORINATED GASES (F-GASES)

As well as contributing to the depletion of the ozone layer, **synthetic fluorinated gases** (colloquially known as **'F-gases'**) are also effective greenhouse gases. There are four main categories of F-gases: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)[7].

Unlike other GHGs, all F-gases are derived from human activities i.e. they are synthetic gases and did not exist in the atmosphere previously. F-gases have a variety of sources, and the proportions of each source has changed over time

[6] Source: https://www.epa.gov/ghgemissions/overview-greenhouse-gases#nitrous-oxide [Accessed: 7 November 2018]

[7] Source: https://www.epa.gov/ghgemissions/overview-greenhouse-gases [Accessed: 3 November 2018]

due to mandated global agreement(s) (e.g. phasing out of chloro-fluorocarbons (CFC's) with the Montreal Protocol) and society demands. Figure 6 outlines the F-gas sources from a US perspective.

F-gases are much more efficient at absorbing infrared radiation than an equal amount of CO_2; hence whilst they are not as volumetrically significant, their efficacy for thermal absorption requires ongoing focus on reducing their accumulation in the atmosphere.

However, to an extent, the regulation of F-gases (specifically CFC's) is a relative success story in how global co-operation and commitment is able to effectively implement the actions required to avert ongoing environmental damage.

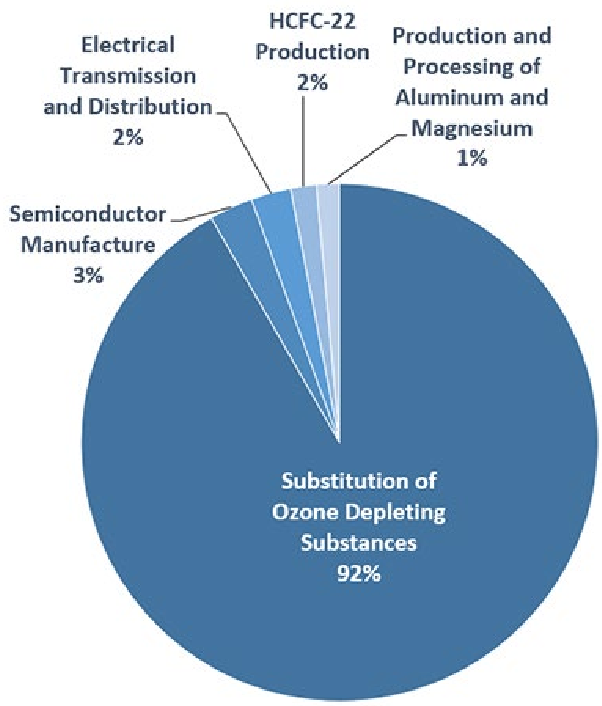

Figure 6   F-Gas emissions by Source, 2016 U.S. (U.S. Environmental Protection Agency)

GREENHOUSE GASES (GHG) AND THE GREENHOUSE EFFECT (GHE)

Greenhouse gases (GHGs) are an integral part of maintaining the Earth's climate and act to regulate the Earth's temperature within a habitable range(s) for life. Without the presence of GHGs in the atmosphere it is predicted that there would be far greater fluctuation in the temperature ranges experienced, with greater extremes during the night and day, and an average global temperatures of -18 °C (compared to the current global average of +14 °C)[8].

From a simplistic perspective the action of GHGs involves these gases trapping re-radiated heat, originally absorbed by the Earth from the Sun, and preventing this heat energy from escaping the Earth's atmosphere. This action is similar to the action of a greenhouse in a garden used to grow plants at a higher temperature than the external environment, hence the term **'greenhouse effect'(GHE)-** refer to Figure 7.

[8] Source: https://climatechange.environment.nsw.gov.au/About-climate-change-in-NSW/Causes-of-climate-change [Accessed: 4 November 2018]

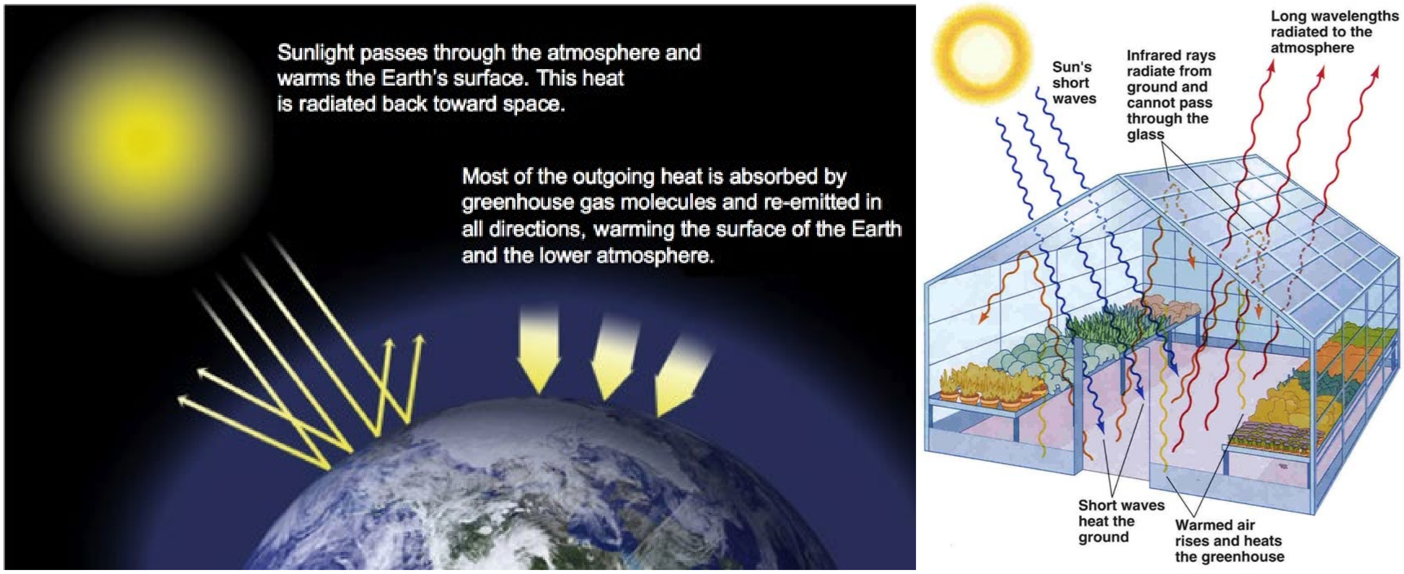

Figure 7 Greenhouse gas effect (GHE)[9] and the action of greenhouse gases (GHG)[10]

To understand the GHE in more detail, however, it is important to understand how the solar energy received by the Earth is dispersed – this process is known as the 'global mean energy budget'. With reference to Figure 8[11], the key parts to this process include:

(1) Incoming solar energy (*incoming solar*) is either reflected directly back into space (*solar reflected*), absorbed directly into the atmosphere (*solar absorbed atmosphere*) or transmitted and either absorbed at the Earth's surface (*solar absorbed surface*) or reflected (*solar reflected surface*)
(2) Of the solar radiation that reaches and is absorbed by the Earth's surface, the majority is re-radiated as infra-red radiation (IR) (*thermal up surface*), with only minor *evaporation* and release as *sensible heat* (forming latent heat in the atmosphere).
(3) This re-radiated energy (*thermal up surface*) is then either released into space (*thermal outgoing*) or trapped by GHGs present in the atmosphere (*thermal down surface*).

A characteristics of GHG molecules is that they can absorb infrared radiation causing them to vibrate. The vibrating molecule will then emit the radiation again, where it will be absorbed by yet another GHG molecule. Subsequently a significant proportion of this re-emitted radiation is trapped and/or transmitted back to the Earth's surface. This absorption-emission-absorption cycle keeps heat near the Earth's surface, effectively insulating the surface from the cold of space.

The greenhouse effect (GHE) is a natural process whereby heat energy provided by solar radiation is retained within the Earth's atmosphere; without it the Earth would be substantially colder than current temperatures.

Greenhouse gases (GHGs) are the key gases responsible for trapping the heat energy re-radiated from the Earth's surface, similar to the action of the structure of a greenhouse – hence the term 'greenhouse effect'.

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[9] Source: http://helios.pomfretschool.org/solar-greenhouse.html [Accessed: 4 November 2018]

[10] Source: https://climate.nasa.gov/causes/ [Accessed: 4 November 2018]

[11] Source: Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: *Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

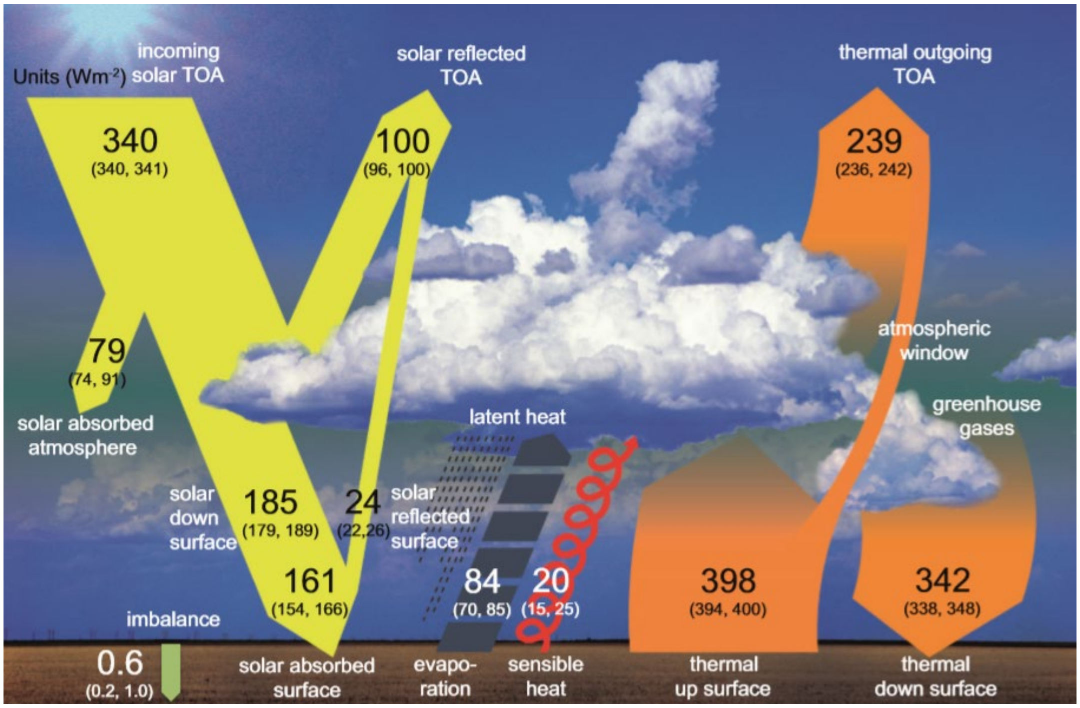

Figure 8 Global mean energy budget (IPCC 2013) [numbers state magnitudes of individual fluxes in W m^{-2}][11].

4.5.2 GREENHOUSE GASES (GHG) & THE ENHANCED GREENHOUSE EFFECT (GHE)

ENHANCED GREENHOUSE EFFECT

The **enhanced greenhouse effect (GHE)** describes the imbalance that has arisen with GHGs in the atmosphere increasing too quickly and has coincided with increased in global industrialization and population growth – a corollary of this growth is CO_2 emissions related to human activity (refer to Figure 2). This increase has upset the natural balance and caused global warming to occur too rapidly for the Earth's environment to adjust.

This increased accumulation results in more **infra-red radiation (IR)** being absorbed in the atmosphere, increasing the overall temperature of Earth – as summarized in Figure 9.

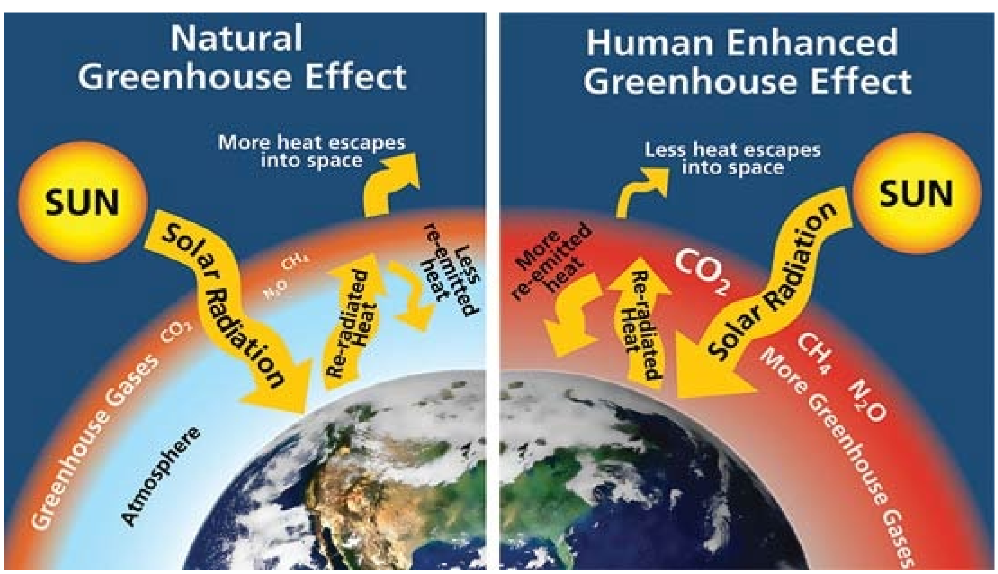

Figure 9 Comparison of the natural greenhouse effect and the human enhance greenhouse effect

CONSEQUENCES OF THE ENHANCED GREENHOUSE EFFECT

The actual and potential consequences of the ongoing trends in climate change may included (but not limited to):

- Increase in frequency and intensity of extreme weather conditions
- Warming of the oceans
- Reduced area and thickness of sea ice
- Rise in sea levels
- Changing ocean current patterns
- Increase in heat-related deaths and diseases
- Releasing methane from ice
- Changing rainfall patterns
- Changes in migratory and reproduction cycles of animals
- Change in natural vegetation and agricultural crops
- Loss of biodiversity
- Decrease in water supplies suitable for human consumption

SUMMARY OF IMPACT OF GHG & CLIMATE

GHGs are an essential part of the regulation of the Earth's climate, without these gases the Earth's climate would be inhospitable for life. However, increasingly evidence has emerged of the adverse impact of increased GHG emissions related, in large part, to man-made activities. An excerpt of the key messages, as outlined by Raupach and Fraser in the CSIRO publication *'Science and Solutions for Australia – Climate Change'* (2011), is presented in Figure 9. This message from the CSIRO, Australia's peak science organization, is further reinforced by the projected temperature changes presented in Figure 10 – data published by the Intergovernmental Panel on Climate Change (IPCC).

Key messages

- Greenhouse gases (GHGs) influence the Earth's climate because they interact with flows of heat energy in the atmosphere.
- The main GHGs influenced directly by human activities are carbon dioxide (CO_2), methane, nitrous oxide, ozone, and synthetic gases. Water vapour, although an important GHG, is not influenced directly by human activities.
- The amount of warming produced by a given rise in GHG concentrations depends on 'feedback' processes in the climate system, which can either amplify or dampen a change. The net effect of all climate feedbacks is to amplify the warming caused by increasing CO_2 and other GHGs of human origin.
- The atmospheric level of CO_2 (the most important GHG influenced by human activities) rose from about 280 ppm in 1800 to 386 ppm in 2009, and is currently increasing at nearly 2 ppm per year.
- CO_2 levels are rising mainly because of the burning of fossil fuels and deforestation. Over half of this CO_2 input to the atmosphere is offset by natural CO_2 'sinks' in the land and oceans, which constitute a massive natural ecosystem service helping to mitigate humanity's emissions.
- To have a 50:50 chance of keeping human-induced average global warming below 2°C, it will be necessary to stop almost all CO_2 emissions before cumulative emissions reach one trillion tonnes of carbon. The world has already emitted more than half of this quota since the industrial revolution, and (at current growth rates for CO_2 emissions) the rest will be emitted by the middle of this century.
- Climate change is a risk management issue – the longer we take to act and the weaker our actions, the greater the risk of dangerous outcomes.

Figure 10 Key messages – Climate Change and Greenhouse Gases (source: CSIRO)[12]

[12] Raupach M. and Fraser P. (2011) 'Chapter 2 – Climate and Greenhouse Gases' in 'Science and Solutions for Australia – Climate Change', Editors: Cleugh H., Stafford-Smith M., Battaglia M. and Graham P., CSIRO Publishing, Collingwood VIC 3066 Australia. Online Edition.

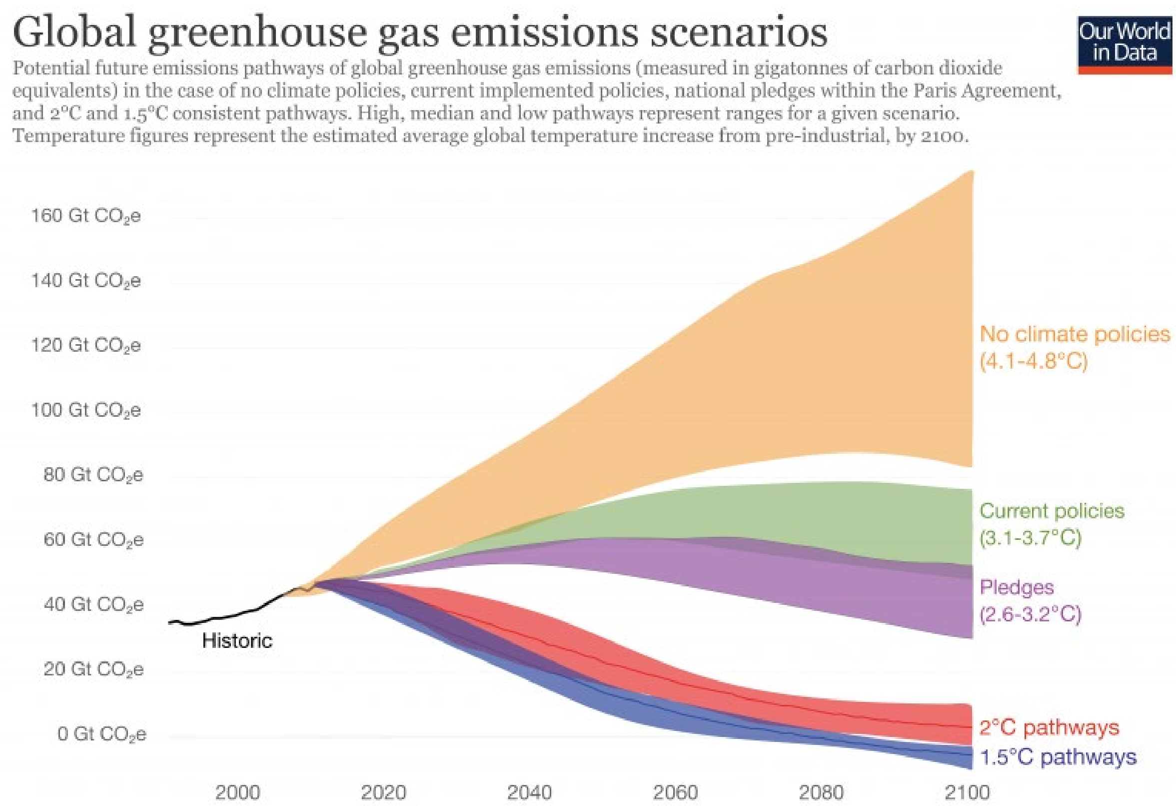

Figure 11 Modelled temperature increases based on global greenhouse gas emissions scenarios[13]

A final word from previous US President Barack Obama (2013)[14]:

> So the question is not whether we need to act. The overwhelming judgment of science -- of chemistry and physics and millions of measurements -- has put all that to rest. Ninety-seven percent of scientists, including, by the way, some who originally disputed the data, have now put that to rest. They've acknowledged the planet is warming and human activity is contributing to it.
>
> So the question now is whether we will have the courage to act before it's too late. And how we answer will have a profound impact on the world that we leave behind not just to you, but to your children and to your grandchildren.
>
> As a President, as a father, and as an American, I'm here to say we need to act.
>
> I refuse to condemn your generation and future generations to a planet that's beyond fixing. And that's why, today, I'm announcing a new national climate action plan, and I'm here to enlist your generation's help in keeping the United States of America a leader -- a global leader -- in the fight against climate change.

[13] https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#greenhouse-gas-emission-sources [Accessed: 7 November 2018]

[14] Transcript of President Barack Obama's speech, Georgetown University announcing his new climate-change policy (June 26, 2013)

KEY LEARNING OUTCOMES (SACE 2018)

From the 'Subject Outline' developed by SACE (2018)[15], the following are the key learning outcomes:

4.4		**Greenhouse Gases & The Atmosphere**	**Check**
	4.4.1	Certain gases in the Earth's atmosphere (known as 'greenhouse gases') produce a phenomenon known as the 'greenhouse effect'	
		Explain how greenhouse gases absorb and reradiate some of the thermal radiation emitted from Earth's surface to warm the atmosphere.	☐

QUESTIONS

Question 1

Define the term 'greenhouse gas'

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Question 2

In the table below, list the key greenhouse gases (GHGs), their percentage contribution to the global GHG emissions and their primary sources.

GHG Gas	% of Global GHG Emissions	Primary sources

[15] Source: https://www.sace.sa.edu.au/web/earth-and-environmental-science/stage-1/planning-to-teach/subject-outline [Accessed: 23 August 2018]

Question 3

Water vapour is also a greenhouse gas (GHG) and is widely produced by human activities. Why does water vapour not accumulate in the atmosphere in the same manner as is evident for the GHGs?

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____

____

____

Question 4

The following questions all relate to the greenhouse effect (GHE)

a) Explain the 'natural' GHE

____

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____

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b) Why is the 'natural' GHE important?

____

____

c) In the box provided, contrast, with aid of a diagram(s), the difference between the natural GHE and the enhanced GHE

Question 5 - Extension

Assessing the impact of greenhouse gases (GHGs) based on their volumetric contribution is only part of the argument. A key factor in determining the contribution of each GHG to global warming is related to a concept known as the **'Global Warming Potential' (GWP).** Refer to the excerpt in Figure 11 and answer the related questions.

In the chart below we see the GWP_{100} value of key greenhouse gases relative to carbon dioxide. The GWP_{100} metric measures the relative warming impact one molecule or unit mass of a greenhouse gas relative to carbon dioxide over a 100-year timescale. For example, one tonne of methane would have 28 times the warming impact of tonne of carbon dioxide over a 100-year period. GWP_{100} values are used to combine greenhouse gases into a single metric of emissions called carbon dioxide equivalents (CO_2e). CO_2e is derived by multiplying the mass of emissions of a specific greenhouse gas by its equivalent GWP_{100} factor. The sum of all gases in their CO_2e form provide a measure of total greenhouse gas emissions.

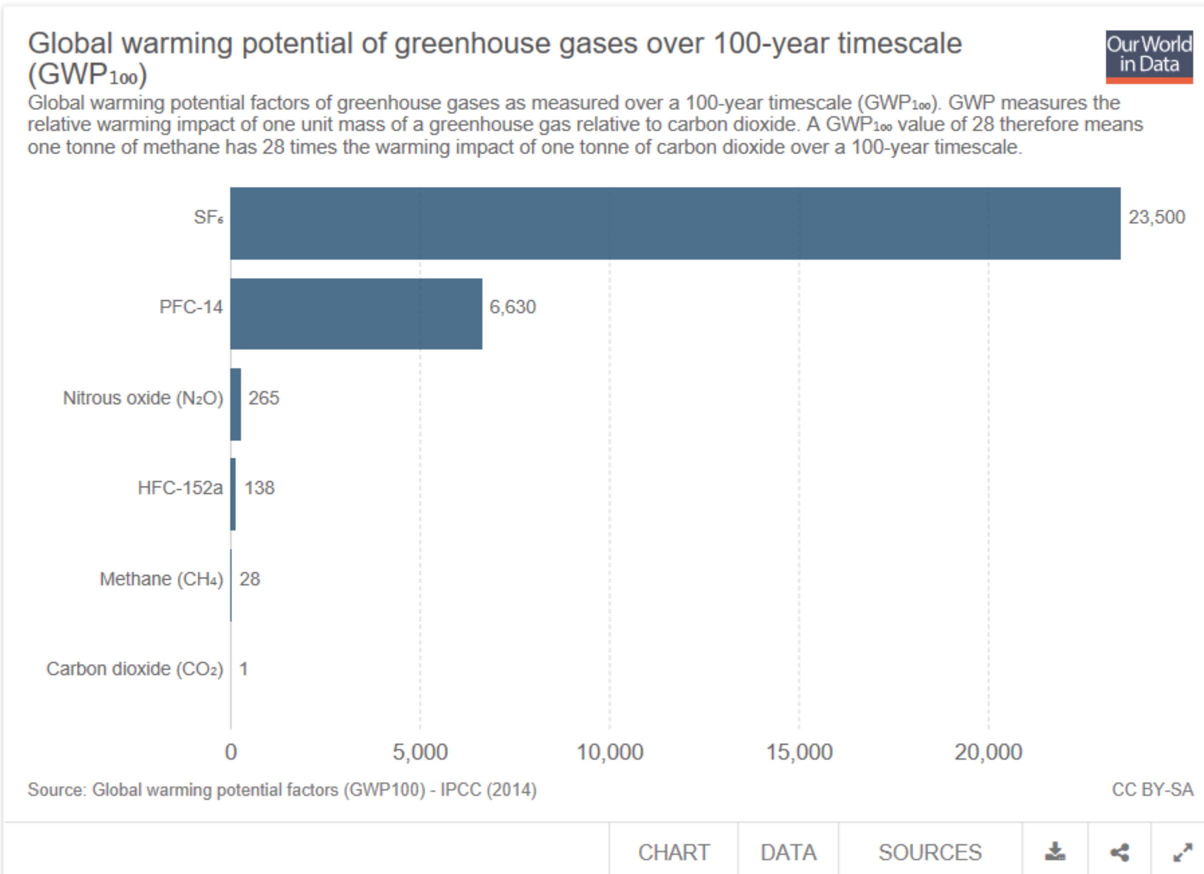

Figure 12 Explanation of Global Warming Potential (GWP)[4]

a) Explain what the concept of Global Warming Potential (GWP) concept involves, and why it is important to consider when evaluating the impact of various GHGs.

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b) Based on your understanding of the GWP concept, do you consider that our society's focus on CO_2, rather than other GHG's, is well-placed if global warming is to be addressed effectively.

Question 6 - Extension

The following is headline related to Australia and our countries commitment to honour the Paris climate change agreement.

Australia will honour Paris climate agreement, Simon Birmingham says

Trade minister fails to name mechanism for emissions reduction as energy policy looms as key issue in Wentworth byelection

a) What is the Paris Agreement? Further research required.

b) How is Australia, as a country, tracking with regard to its commitments under the Paris Agreement and emissions targets? Further research required.

Question 7 - Extension

After reviewing the following videos answer the following questions:

https://www.youtube.com/watch?v=jlyot5PoCUQ

ABC News (Australia)
Published on Jun 27, 2017

Climate scientists rarely speak publicly about their personal views. But in the wake of some extreme weather events in Australia, the specialists who make predictions about our climate reveal they're experiencing sometimes deep anxieties.

https://www.youtube.com/watch?v=pJ1HRGA8g10

BBC Newsnight
Published on Oct 8, 2018

a) Do you think Australians are aware of the potential impacts of climate change? Why or why not?

b) What actions do you think Australia, as a developed nation, should be taking, or not, to reduce GHG emissions?

DEBATE INDUSTRIALISATION VS SUSTAINABLE ENVIRONMENT – COEXISTANCE, IS IT POSSIBLE?[16]

Rising giants debate

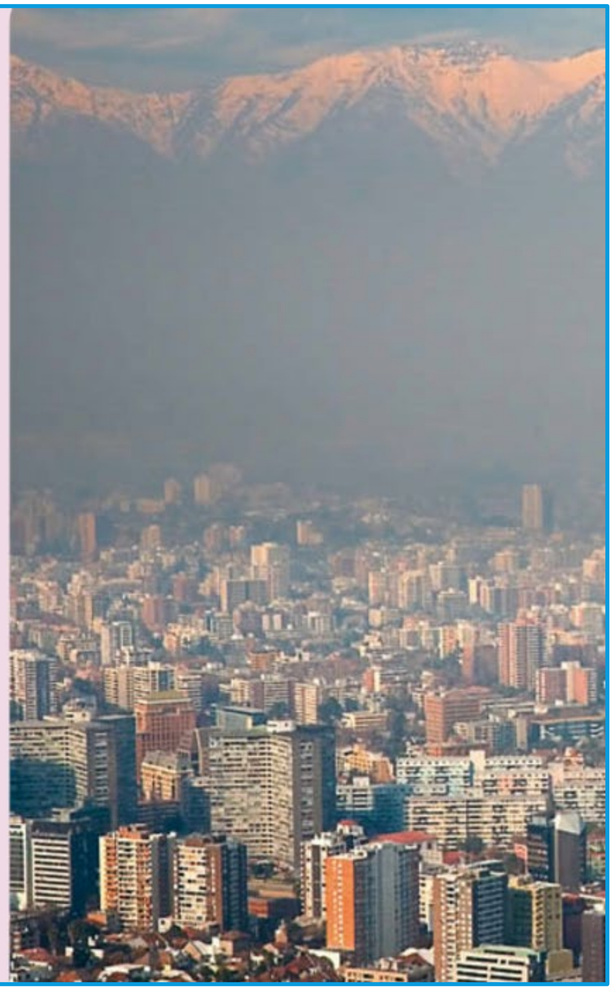
Greenhouse gases increase the ability of the Earth's atmosphere to trap heat from the Sun. Significant warming of the planet could have detrimental effects for life as we know it. Should developing countries with massive populations, like India and China, be expected to reduce their greenhouse gas emissions?

According to recent reports, China's national greenhouse gas emissions may now exceed those of the United States. It is thought that greenhouse gas emissions from developing countries will result in a climate crisis within a generation—within 20 years these countries will be producing more greenhouse gases than the rich industrialised countries. For these developing countries, thinking about reducing their emissions is difficult, due to costs. They have incomes far below those in developed countries and have a need to grow and offer their people a better quality of life, like we experience here in Australia.

1 In groups of six to eight, split into two debate teams.
2 The first team is to argue against developing countries reducing their greenhouse gas emissions because it is their right to become fully industrialised, as well as to eradicate poverty, even at the cost of the environment.
3 The second team is to argue for developing countries reducing their greenhouse gas emissions. This team will argue that environmental sustainability is the most important factor in the debate.

Further research will need to be conducted to ensure that the arguments being made are valid and based on evidence.

- Which team had the most convincing arguments?



ANIMATED ONLINE CLIMATE MODELS

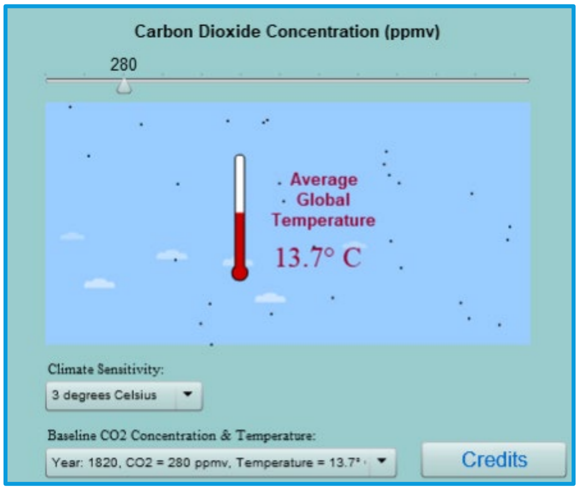
Access available online simulation tools provided, to further understand how the Earth's climate has undergone change, particularly since the late 1950's.

[16] Excerpt from: Quinton G., Cash S., Tilley C., Craven E., Laidler G. and Kennedy E. (2012) *Oxford Big Ideas Australian Curriculum Science 10'* p.109, Oxford University Press VIC 3205 Australia

Allows the user to investigate changes in sea ice, CO_2 and global temperatures over selected time periods; also includes graphics showing impacts of sea level rises.

https://climate.nasa.gov/interactives/climate-time-machine

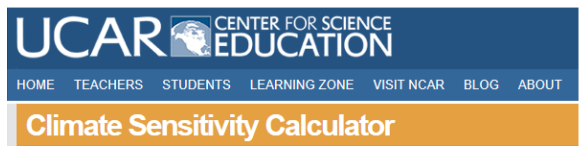
[Accessed: 7 November 2018]

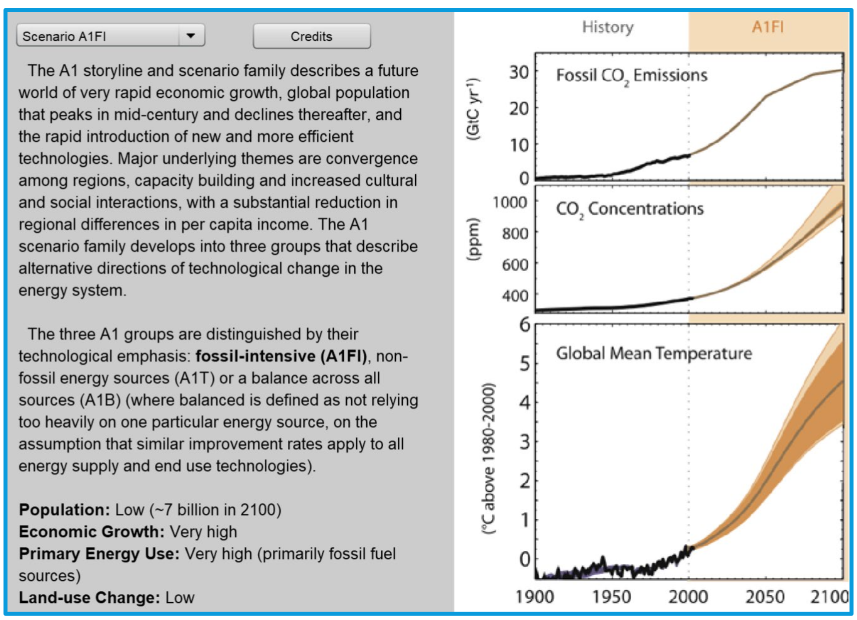


Allows the user to investigate the relationship between levels of CO_2 in the atmosphere ad average global temperatures.

https://scied.ucar.edu/climate-sensitivity-calculator

[Accessed: 7 November 2018]



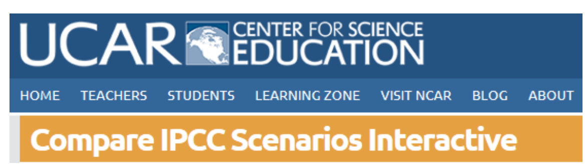


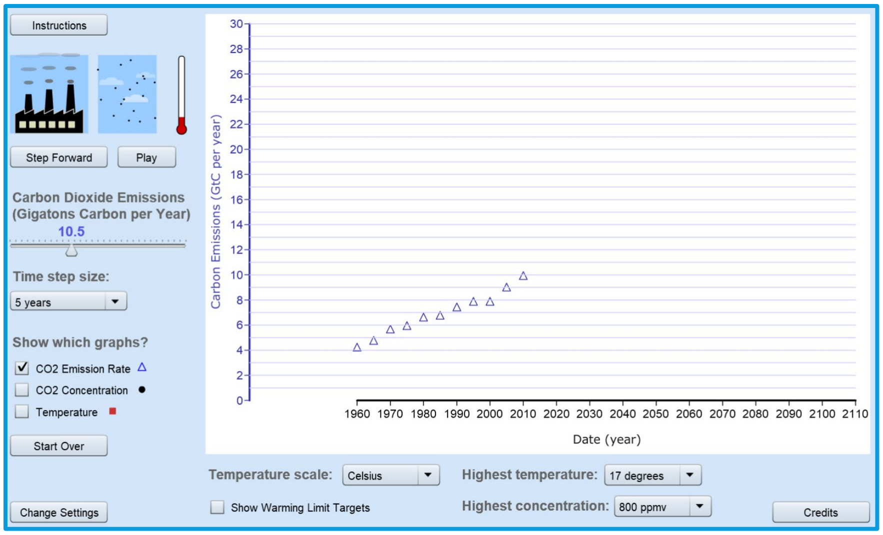
'The Intergovernmental Panel on Climate Change (IPCC) recognizes that future human behaviors will play a large role in determining how Earth's climate changes over the coming century.'

This interactive illustrates the six (6) primary scenarios used by the IPCC.

https://scied.ucar.edu/compare-ipcc-scenarios-interactive

[Accessed: 7 November 2018]





Interactive tool to allow students to investigate the relationship between CO2 emissions and future temperature scenarios

https://scied.ucar.edu/simple-climate-model

[Accessed: 7 November 2018]

Teaching Materials:

https://scied.ucar.edu/activity/very-very-simple-climate-model-activity

KEY TERMS

Greenhouse gases (GHGs), greenhouse effect (GHE), anthropogenic, natural greenhouse effect, enhanced greenhouse effect, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated gases (F-gases), 'Great Acceleration Event', global warming potential (GWP).

4.6 The movement of atmospheric air masses, due to heating, cooling, and the Earth's rotation, causes systematic atmospheric circulation; this is the dominant mechanism for the transfer of thermal energy around the Earth's surface.

- Explain how convection currents promote atmospheric circulation.
- Explain how convection cells promote atmospheric circulation in each hemisphere.
- Explain how the Coriolis effect influences wind direction around the Earth.
- Explain how the movement of atmospheric air masses influences local ecosystems.

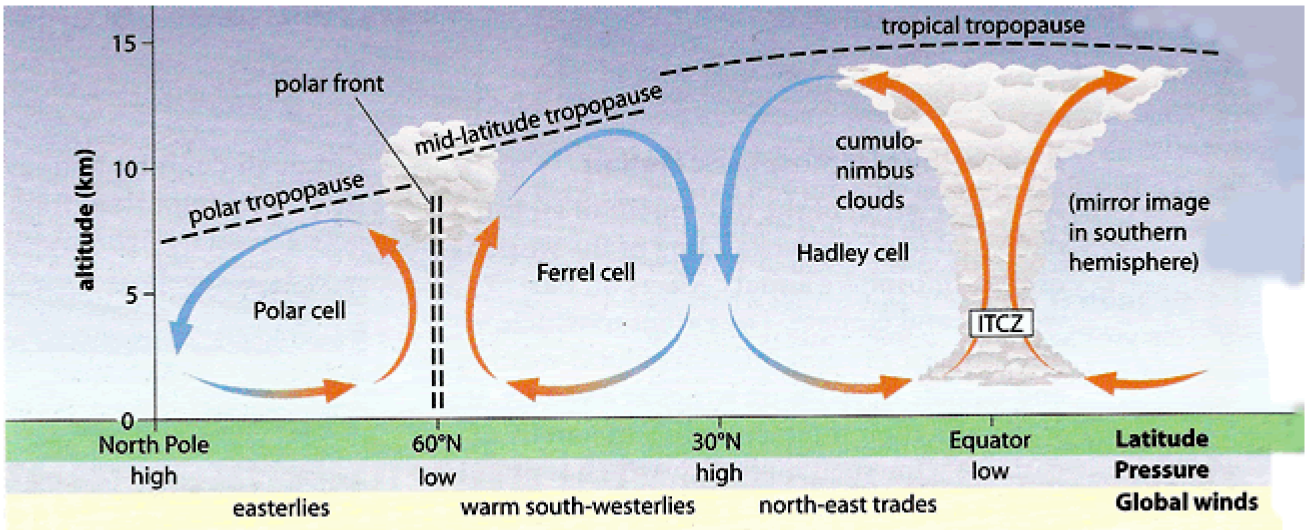


Figure 1
http://static2.mbtfiles.co.uk/media/docs/newdocs/as_and_a_level/geography/physical/atmosphere_and_weathering/1207292/html/images/image00.gif

The image above shows the pattern of convection currents in the atmosphere and the circulation of the air at various latitudes. Convection currents drive the rise and fall of air in the atmosphere as a result of cooling and warming of air masses. This atmospheric circulation plays a key role in the global distribution of precipitation and evaporation. In some regions there is dry convection which involves bulk movement of air without condensation and is in the lower part of the atmosphere particularly in arid regions.

In other regions moist convention includes the effects of cloud condensation and evaporation which can add heat or delete it from the surroundings. Moist convection is an energetic process that alters the environment. In the atmosphere it creates large thunderstorms such as in tropical regions in low latitudes.

View this video https://youtu.be/Ye45DGkqUkE on global atmospheric circulation.

There is a pattern across the earth as a result of these atmospheric cells which are named Hadley, Ferrel and Polar. The earth's climate system is driven from the equator. This is the hottest part of the earth due to being closer to the sun and receiving more solar energy.

As the air rises at the equator (refer to figure 1), this leads to a **low pressure and rainfall.** The air travels to the north or south and **becomes colder and denser** creating a **high air pressure and dry conditions** around 30^0. Air will also rises at 60^0 north and south and will descend at 90^0 north and south. The air masses because of **pressure differences** create **prevailing winds.** The direction of these winds will also be affected by the spinning of the earth or Coriolis effect. The air circulated in the Hadley cell completes the cycle and flows back towards the equator as **trade winds**.

View this video. https://www.britannica.com/science/Coriolis-force/media/137646/112178

Key ideas covered by video:

1. Shows the re-entry of the space craft and highlights the different layers of the atmosphere
2. An easy explanation of air pressure
3. Demonstrates the amount of sunlight that hits surface of earth
4. Demonstration of using dry ice to show cold air falling
5. Visual demonstration of water and air circulation showing convection currents
6. Earth's spin causes air to move faster at equator and shows Coriolis effect on wind direction.
7. Local climate how wind is affected by topography
8. Human habitation affects atmosphere

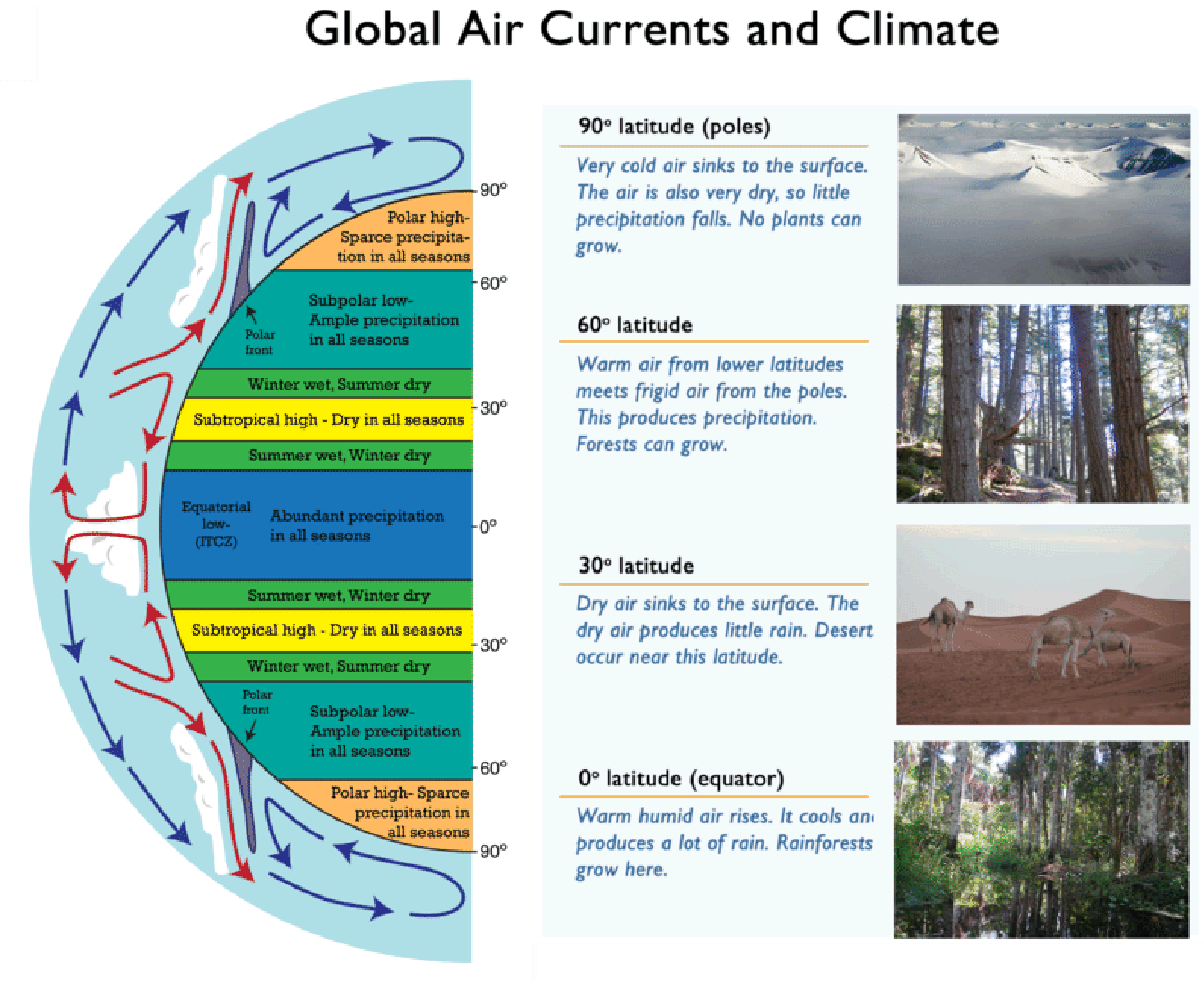


Figure 2 *https://dr282zn36sxxg.cloudfront.net/datastreams/f-d%3A839402e286ce924b290763d2b02d11d8dbbd5f1563e9137d4925c5d3%2BIMAGE_TINY%2BIMAGE_TINY.1*

These atmospheric circulation cells create the **general climate at various latitudes.** The climate created determines the **type of ecosystems** in that region. At low latitudes either side of the equator land masses will have tropical ecosystems with rainforests.

The major factor influencing on climate is atmospheric air masses but there are other factors such as topography which has an influence on climate locally. An example of this is in a location with mountain ranges that may create climate for a subtropical rainforest on one side and desert on the other.

View this video on five factors effecting climate. https://youtu.be/E7DLLxrrBV8

Worksheet Questions.

1. Name the three atmospheric circulation cells.
2. How does the concept of convection currents apply to the earth's atmosphere? What causes the convection currents? How does this then influence the climate in a regions?
3. Explain the factors that determine the direction of prevailing winds?

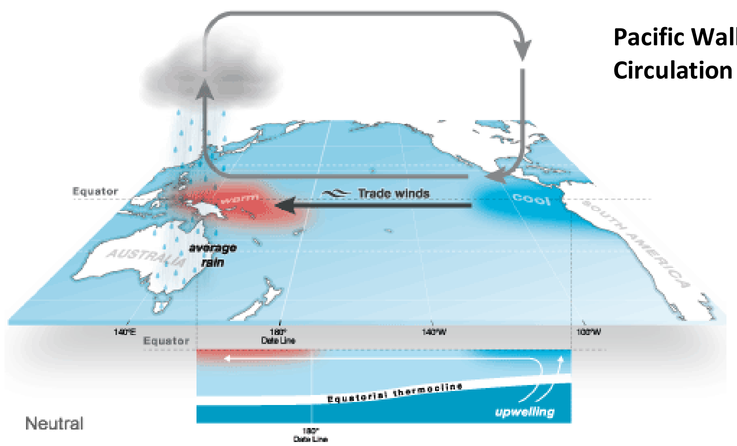
4.7 The interaction between the Earth's atmosphere and oceans changes over time and can result in anomalous global weather patterns.

• Discuss the causes and effects of ENSO (El Niño–Southern Oscillation).

Normally or in the neutral setting strong trade winds blow from the east along the equator, pushing warm water into the western Pacific Ocean.This **warm sea surface temperature** pumps heat and moisture into the atmosphere. As a result of atmospheric **convection** the warm air rises, forms cumulonimbus clouds and rain and in the **east drier air descends.** This pattern of air circulation is called the Pacific Walker Circulation. Refer to figure 1 below
This process is also driven by ocean currents. In the picture below is shown a line called a **thermocline** which marks the transistion between warm upper water and cold deeper water in the Pacific ocean. If the thermocline is closer to the water surface the result is upwelling of the cold nutrient rich deep water. This upwelling causes **cooler temperatures at the water surface**.

Pacific Walker Circulation

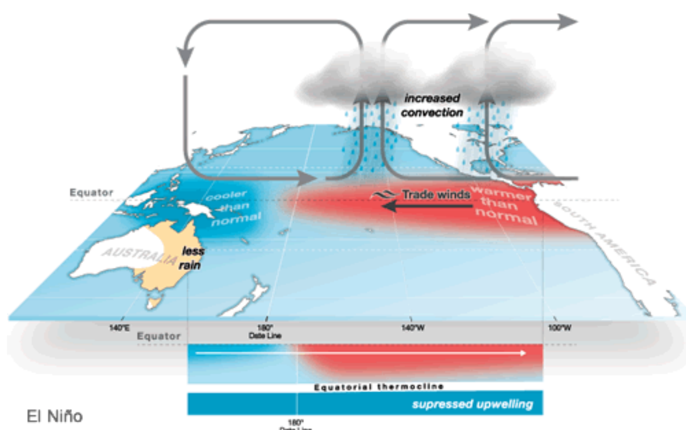
West



East

Figure 1 http://www.bom.gov.au/climate/about/australian-climate-influences.shtml?bookmark=enso

El Nino (figure 2) conditions occur when abnormally **warm waters** accumulate in tropical latitudes of the central and eastern Pacific Ocean associated with a **weakening of the low-level easterly winds**. Consequently, tropical rains that usually fall over Indonesia shift eastward. This results in Australia having an increase in temperature and decrease in rainfall. This change in climate means heat waves and increased risk of drought and bushfires. There is also a later start to Australia's Northern wet season with fewer cyclones and reduced chance of widespread flooding.



La Niña conditions occur when cooler-than-average waters accumulate in the central and eastern tropical Pacific, associated with a strengthening of the low-level easterly winds over the central tropical Pacific. Heavy rainfall occurs over Indonesia and Malaysia.

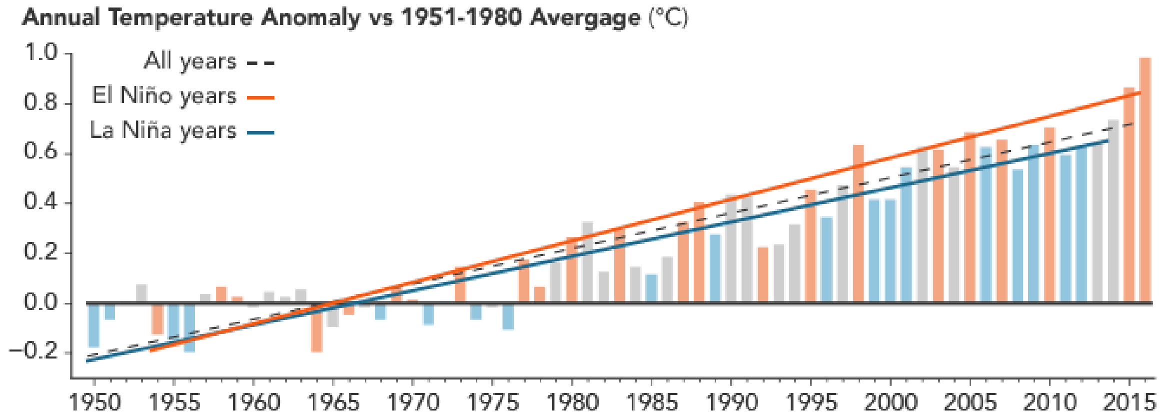


Figure 3

The graph above illustrates that in El Niño years that the annual temperatures are higher and during La Nina annual temperatures are lower. It also shows that patterns of these events are irregular.

In fact El Niño events occur up to a few times per decade and are of very variable intensity. Detailed knowledge of the shape, area, position, and movement of the warm water can be provided from satellite derived data to help study the phenomenon and forecast its consequences.

Adding to this knowledge is the use of the Southern Oscillation Index (SOI) which is a measure of the intensity or strength of the Walker Circulation. It is one of the key atmospheric indices for gauging the strength of El Niño and La Niña events and their potential impacts on the Australian region. Refer to this link to view data collected and graphed.

http://www.bom.gov.au/climate/model-summary/#region=IOD&tabs=Bureau-model

The SOI measures the difference in surface air pressure between Tahiti and Darwin. The index is best represented by monthly (or longer) averages as daily or weekly SOI values can fluctuate markedly due to short-lived, day-to-day weather patterns, particularly if a tropical cyclone is present.

Worksheet questions

1. What are the 3 phases of the ENSO?
2. Explain how an El Niño occurs and how it might impact on the weather patterns in Australia.
3. What can be said about the predictability of El Niño events in the future?
4. What information is collected by scientists to provide information about El Niño events?